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Researching Technology Improvements for AIS

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Researching Technology Improvements for AIS

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16. Abstract (MAXIMUM 200 WORDS) The international Automatic Identification System is used by the USCG and Marine Exchange of Alaska to monitor marine traffic navigating the coast of Alaska. This report is a summary of findings concerning methods for extending AIS surveillance coverage through the deployment of remote equipment where both AIS channels are used to acquire AIS messages and relay those messages to existing facilities. Added to the relayed messages are separate measurements of each AIS message. Additional objectives include cyber-attack resistance, maintaining the integrity of the AIS channels, and reduction of deployment and operating costs. The investigation included the design and construction of proof-of-concept equipment with custom software capable of being used in the laboratory, field trials, and demonstrations to test and evaluate the effectiveness of the different methods and options. This effort also considered methods beyond current AIS technology. New signal and data structures were developed and implemented. This results in an ability to partially recovery information from AIS messages normally discarded due to corruption from radio noise and interference. This work concluded with delivery of the proof-of-concept equipment and software. The next phase would be laboratory testing of the methods, upgrades to the methods based on laboratory results, and planning for field tests to determine the operational range compared against standard AIS equipment, such as, store-and-forward repeaters.					
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EXECUTIVE SUMMARY

The operational range of Automatic Identification System (AIS) devices is intentionally limited by the radio frequencies and power levels chosen for the service. The reliability of the marine navigation information the AIS provides improves as the distance between units decreases, while signals from units separated by the radio horizon do not interfere. Authorities who use the AIS signal for surveillance use different methods to extend the radio horizon of their AIS facilities. This report describes research equipment and software that gathers and conveys AIS messages using only the AIS frequencies and provides a variety of optional methods. Added to each message are separate measurements of the message. The combined information is then broadcast using a single AIS compatible radio packet. The additional information about the message could be used to detect and manage the content of AIS messages from malfunctioning AIS units or other questionable sources. It can also be used to monitor the health of the system, itself.

The delivered equipment is designed for laboratory use; but should be sufficiently durable for controlled field tests and demonstrations. The equipment consists of two major sub-systems shown in Figure ES-1. The first sub-system is the equipment intended to be deployed at a remote location (rebroadcast site – left of the figure). It is designed to gather and rebroadcast information using only the AIS channels, in particular AIS Message Type 26 (i.e., multiple slot binary message). The second sub-system is the equipment that would be deployed to an existing surveillance facility (surveillance site – right of the figure).

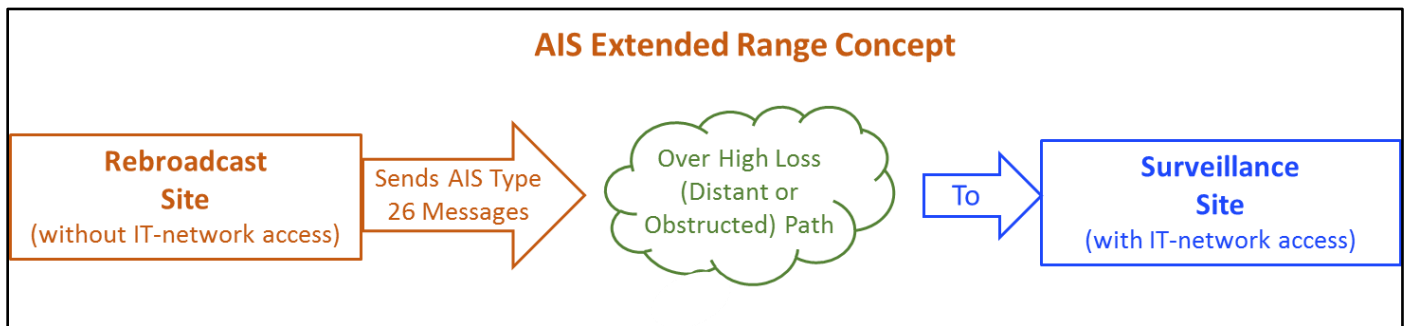


Figure ES-1. Notional concept of extended range AIS.

The signal level needed to overcome the radio noise at the surveillance site limits the maximum separation between rebroadcast and surveillance site equipment. Transmission methods are introduced to improve weak signal reception. In addition to power and antenna gain, the delivered capability provides the ability to experiment with four duplicate message transmission options for combating radio noise. The duplicate message methods introduce a signal structure that supports the partial or total recovery of information from noise-corrupted messages. The four options are:

- **Time**, transmit two copies of the same message using different VDL “slots;”
- **Frequency**, simultaneously transmit two copies of the same message on both AIS channels;
- **Antenna polarization**, transmit one copy of a message using vertical polarization and the second copy of the message using horizontal polarization; and
- **Radio path**, simultaneous reception using multiple antenna-receiver combinations.

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The rebroadcast equipment includes two independent transmitters. The two transmitters are used to transmit duplicate copies of the same information. This supports the simultaneous comparison of different option combinations.

The AIS design adopted the International Organization for Standardization (ISO) synchronous framing method to code and convey information bits in the AIS radio signal. This method causes the number of bits in the AIS radio packet to be variable, depending on the bit-coding of the data content. The added synchronous framing bits and data bits can cause reception issues when the signal is affected by noise. This report describes a method, which is fully AIS compatible, for circumventing the issues created when demodulating an AIS radio packet that uses synchronous framing in the presence of noise.

As the radio packet strength weakens, reception noise will corrupt the output of the receiver's demodulation process. By design, current AIS equipment internally discards corrupted messages. Commercial AIS equipment does not provide an option to externally view corrupted messages. Therefore, use of existing AIS equipment limits the depth to which the relationship of AIS signals to local noise issues can be studied and remedies decided. This report discusses how the delivered equipment was upgraded to provide these messages and how repair or partial recovery of message information using data processing methods external to the receiver is possible.

The results of initial laboratory tests concludes that some and possibly all the information of interest in a corrupted AIS radio packet may be directly recovered or indirectly repaired using additional digital data processing methods. This discovery improves the effective sensitivity of an AIS receiver, and improved sensitivity extends the limit at which a rebroadcast site can be located relative to a surveillance site.

This research goes beyond current AIS technology. It enables more detailed study of Very High Frequency Data Link (VDL) activity and the nature of message corruption; and it transitions the analysis of the AIS radio-link to software defined radio methods. This enables the investigation of cybersecurity threats and the effectiveness of countermeasures using both defensive and offensive methods. This information will be important in defining the next generation of AIS.

The topics recommended for further consideration and action are:

- 1) AIS 2.0: Initiate and support an international review of AIS collision avoidance and cybersecurity issues to launch the effort to define the technical requirements for the next generation of AIS technology. (This work begins inside the committees and working groups of International Maritime Organization (IMO), International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), and International Electrotechnical Commission (IEC)).
- 2) Establish a working group and document surveillance requirements for an AIS shore infrastructure. (This working group should include the organizations who currently use, or react to, the surveillance information and those who operate surveillance networks – United States Coast Guard (USCG), United States Army Corp of Engineers (USACE), and Marine Exchange of Alaska (MXAK)).
- 3) Continue AIS radio-link research into performance enhancement methods, supporting all other topics recommended in this section, and that may fundamentally and positively impact all uses of AIS (USCG Research and Development Center (RDC)).
- 4) Initiate AIS VDL integrity monitoring research. (RDC working with issues provided by operators of shore surveillance infrastructures – Nationwide AIS (NAIS), USACE, and MXAK.)



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- 5) Initiate exploration of “AIS-friendly” methods that enhance the use of AIS for communications. (RDC working with Command Control Communications Computers Information Technology (C4IT) Office).
- 6) Investigate defensive and offensive real-time cybersecurity methods and countermeasures for use with both current AIS technology and the next generation of AIS. (RDC working with USCG representatives to IMO, IALA, and IEC; also, linked to topic “4” effort; and following Department of Homeland Security (DHS) direction to defend critical maritime infrastructure.)



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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AIS	Automatic Identification System
AIS1	AIS channel A or 161.975 MHz.
AIS2	AIS channel B or 162.025 MHz.
ANSIS	Arctic Maritime Navigation Safety Information System
AtoN	Aid to Navigation
AWGN	Additive White Gaussian Noise
BER	Bit error rate
C4IT	Command Control Communications Computers Information Technology
Comm	Communications
CRC	Cyclic redundancy check (CRC-16-CCITT, see ISO/IEC 13239:2002)
dB	decibel
dBm	Decibel-milliwatts
DHS	Department of Homeland Security
EEZ	Exclusive Economic Zone
FCS	Frame check sequence (ITU-R-REC-M.1371, see CRC)
FM	Frequency Modulation
GMDSS	Global Maritime Distress Safety System
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HDLC	High-level data link control
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
ID	identification
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ISO	International Organization for Standardization
ITDMA	Incremental Time Division Multiple Access
ITU	International Telecommunications Union
LFA	Loop Fed Array
MMSI	Maritime Mobile Service Identity
MOI	Message of interest
MTS	Marine Transportation System
MXAK	Marine Exchange of Alaska
NAIS	Nationwide AIS
NMEA	National Marine Electronics Association
PC	Personal Computer
PI	Presentation Interface
PER	Packet error rate
POSIX	Portable Operating System Interface for uni-X



LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

RDC	USCG Research and Development Center
RDC	(USCG) Research and Development Center
RX#	Receiver number
SBIR	Small Business Innovative Research
SDR	Software Defined Radio
SOTDMA	Self-Organizing Time Division Multiple Access
USACE	United States Army Corp of Engineers
USB	Universal Serial Bus
USCG	United States Coast Guard
UTC	Universal Time Coordinate
VDL	Very High Frequency Data Link
VHF	Very High Frequency
VTs	Vessel Traffic Services



1 INTRODUCTION

The United States Coast Guard (USCG) “Next Generation Arctic Maritime Navigation Safety Information System (ANSIS)” is investigating improvements to technologies used by mariners operating in the U. S. Arctic Exclusive Economic Zone (EEZ). Working in conjunction with the Marine Exchange of Alaska (MXAK), the ANSIS project seeks alternatives for improving the acquisition and distribution of important, time-critical, information to and from mariners. This investigation includes Automatic Identification System (AIS) technology used by MXAK to acquire and distribute information. The ANSIS project also seeks to develop technologies that require less infrastructure to support (e.g. remote locations in Alaska).

The AIS is an internationally agreed and globally deployed technology used by mariners to automatically exchange important navigation information between ships, and between ships and shore facilities [1]. In general, the range of AIS signals in the arctic is limited to line of sight between ships and shore stations with a typical operating range of 20 nautical miles (nm). The desire is to reliably extend the typical range for surveillance beyond that of sensors used today (e.g., surveillance radar, standard AIS, and cameras) into wider areas. Throughout this report, “surveillance” is used in the broadest sense of the word; general monitoring and tracking as used by the USCG in Vessel Traffic Service [2-3]. This report describes: methods proposed to improve the performance of the AIS radio link; and the progress in developing the tools needed to test and measure the performance of the proposed methods along with some preliminary results.

This report also looks at the surveillance information that is lost when using current International Electrotechnical Commission (IEC) standard AIS repeaters [4]. Also, a new rebroadcast method is described which uses an experimental AIS message. The purpose of the new rebroadcast method is to provide a more resilient signal, thus improving the radio-link; and an expanded information content which is of more value to surveillance operations than the information provided by a repeater. This combination should improve the integrity and value of repeated messages and suppress some cyber-security issues associated with shore surveillance.

This report also presents four improvement methods that are still outside the standard AIS “box.”

1. Repair of messages failing the Cyclic Redundancy Check (CRC).
2. Elimination of message “stuffing” bits.
3. Use of both vertically and horizontally polarized signals.
4. Modified slot use rules.

The completed equipment upgrades are now able to support further testing of these methods. These methods are expected to improve the radio-link performance (bit repair/partial packet information recovery, and an increase of information bandwidth using polarization multiplexing and simultaneous transmissions on the same slot).

While some of the improvement methods are outside standard AIS, care has been taken in their design and implementation that standard AIS operation will not be affected by their use.



1.1 Overall Objective

Improving the performance of the AIS radio-link between equipment at fixed locations is the objective of this work. Can the radio-link performance be improved? The work thus far suggests that it can. In particular with the engineering requirements shifting from AIS being transmitted from moving platforms to use for point-to-point communication.

In addition to improving the operational performance of the radio-link itself, this report considers the additional message-information that an AIS receiver should provide; and how that information can be conveyed to essentially extend the infrastructure's integrity and cybersecurity requirements [5] through the radio-link (false information, denial of service, and information intended to mislead). Put another way, remote repeaters designed to support surveillance need to provide the same information quality and integrity as the surveillance infrastructure to which they are intended to support.

Figure 1 shows a 2013 example of vessel locations (colored squares, diamonds, triangles, and circles) and locations (boxes) where the MXAK installed ("i") or planned to install ("o") AIS receivers. In order to consolidate and then distribute information, the MXAK needed connections to IT network services at each receiver location. In Alaska, finding and sustaining locations where all the needed support services converge (i.e., power and IT infrastructure) to cover an area of marine interest is a challenge and can be costly. This report considers using the AIS radio-link to replace the need for IT network services at some receiver sites. In particular, when the receiver site is used to monitor an area with low vessel traffic.

Surveillance of either remote archipelago areas or distant vessels in a high vessel traffic area, suffer from two basic forms of signal blockage. In the archipelago physical signal attenuation is caused by land mass, such as, hills and mountains. Distant weak signal reception in an area with a high concentration of AIS units suffers from strong signal interference from the local AIS units. This is particularly noticeable when AIS is used for mobile to shore communications. An example of signal blockage is shore reception of off-shore vessels operating among the towers in the Gulf of Mexico whose weaker AIS signals are obscured by the signals from coastal waterway traffic. In both cases, rebroadcast methods could improve the performance of the AIS radio-link.

Finally, the current AIS repeater design was developed by IEC to satisfy navigation requirements. These requirements are not the same as surveillance requirements. This report considers how the two sets of requirements differ, in particular with respect to cybersecurity and to reduce bandwidth requirements. The surveillance community needs to consider drafting a separate set of AIS surveillance requirements that would guide future development of AIS rebroadcast technology. Public discussion of AIS cybersecurity issues would also be helpful in advancing the development of the next generation of AIS equipment standards.



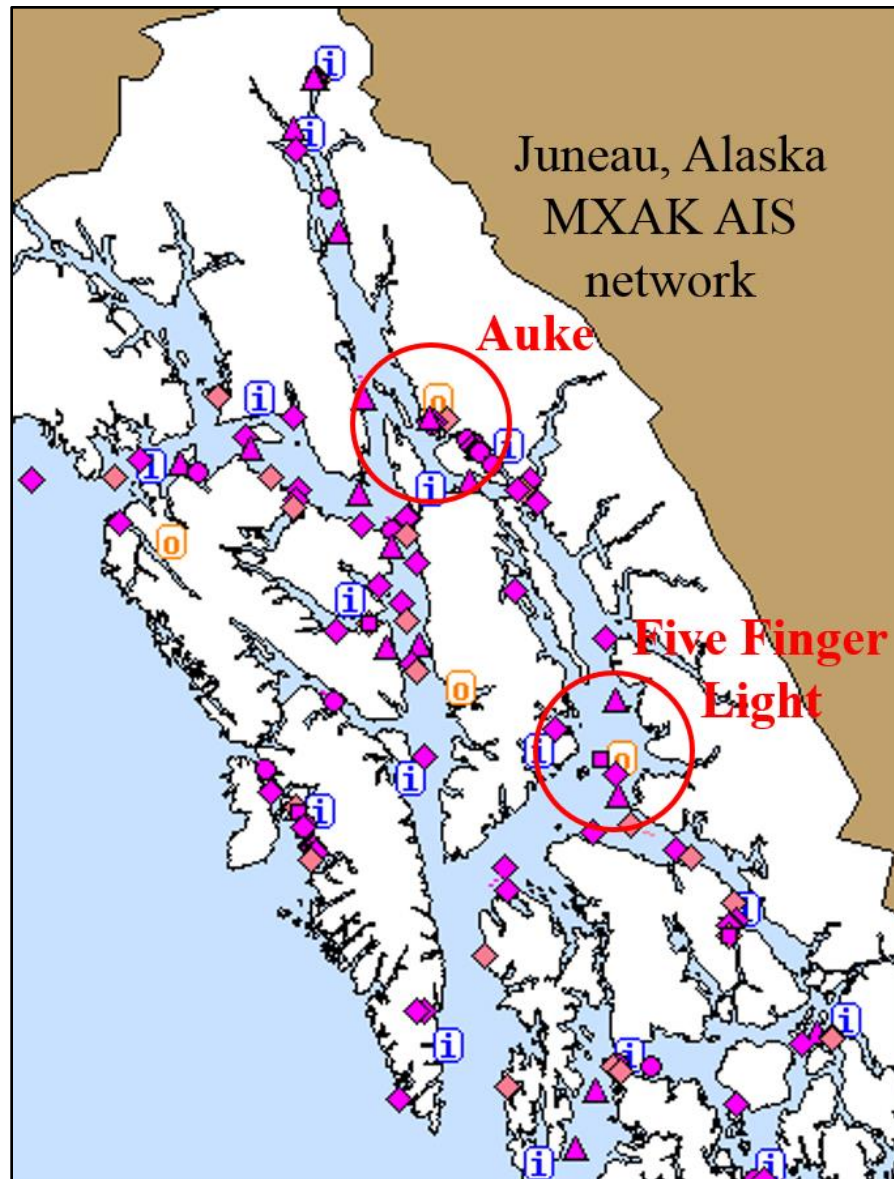


Figure 1. “Snapshot” of vessels in the northern Alexander Archipelago, Alaska, and MXAK receiver sites (See text).

Figure 2 shows the combined reception resulting from two key MXAK sites – located at Auke and Five Finger Light. The approximate division of the two coverage areas is shown by the violet line in Figure 2. The various colors in the waterways indicate the concentration of AIS reports received over the 24-hour period of 1 August 2013 (red is most concentrated and blue is least concentrated). While these two sites provide the bulk of the needed surveillance coverage, there remain “blind” spots – areas where no or a low concentrations of reports are received. In order to extend coverage, fill gaps, or extend coverage into obscured areas, the current method is to install a complete reception site including an IT service connection. Some of the receiver locations shown in Figure 1 are installed to fill small coverage gaps.

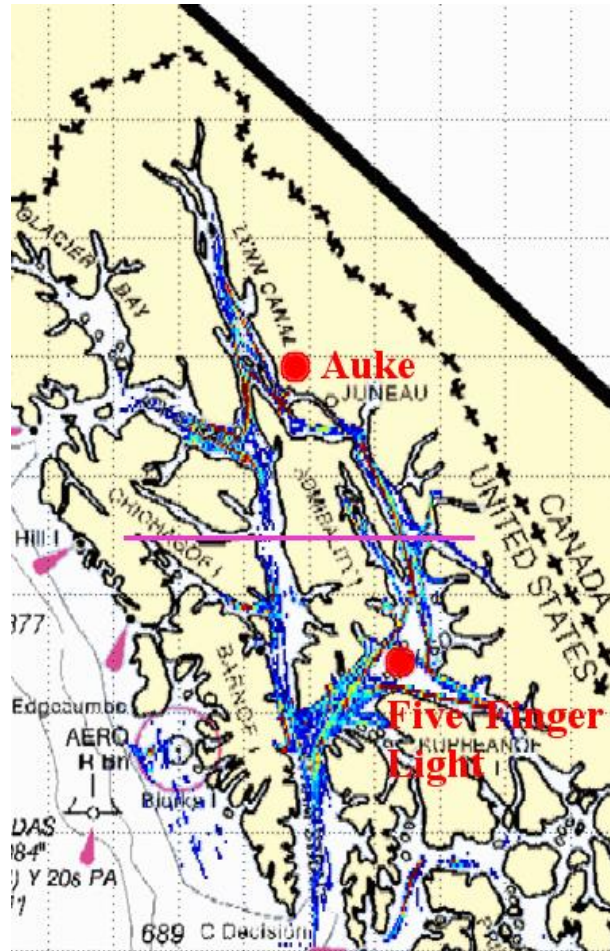


Figure 2. Combined AIS coverage of MXAK Auke and Five Finger Light, August 1, 2013 (See text).

1.2 Background

AIS was established by the International Maritime Organization as a technology intended to improve collision avoidance and support an authority's ability to monitor marine traffic. Besides being used by mariners to make navigation decisions, AIS provides real-time maritime situational awareness useful to vessel traffic services and search and rescue operations. Because AIS information is shared in real-time, it can be used for live management of marine traffic, security, and emergency operations [6].

The distance at which AIS signals can be reliably received is limited by design to approximately a ship's radio horizon – spatial diversity. This limitation allows the technology to be spectrum efficient (utilizing only two radio channels worldwide) while simultaneously being used by hundreds of ships without performance degradation.

Through an upgrade to its infrastructure and in cooperation with similar efforts by the U. S. Army Corp of Engineers (USACE) and the Marine Exchange of Alaska, the USCG is able to gather AIS-based information from vessels operating along the U. S. coast and inland waterways. However, there remain areas where the installation and maintenance of 24/7 surveillance facilities is expensive and logistically difficult, in particular, along the coast of Alaska.



In addition to operational and logistical issues, every additional surveillance facility introduces added cyber-security issues, in particular, if the facilities are linked with commercial IT network services. Extending surveillance using only the AIS radio-link for communications may provide a less vulnerable and less expensive information path than using commercial IT network services. This is dependent on the existing VDL loading from standard AIS operation. Also, the elimination of commercial IT network equipment may reduce electrical power requirements to a level where full operation is possible using an alternative energy source, such as, the proven solar/battery system on USCG buoys.

Extending the distance at which AIS messages can be received has been the subject of AIS equipment standards authored by the International Electrotechnical Commission (IEC) and experimentation and demonstrations conducted by the USCG RDC [7-9]. The IEC has published a simplex repeater standard (IEC 62320-3) where the repeater logic is designed around the requirements for safe navigation and collision avoidance. The IEC defined repeater standard does not fully exploit all the options available for improving surveillance radio-link performance (See Appendix A.). The USCG RDC's long range reception research centered on improving surveillance by the development and deployment of improved radio reception technology on different persistent platforms, such as, buoys, towers, mountain tops, and satellites. The USCG research also helped the international community develop methods for adding surveillance information to each received AIS message. Until this task, the USCG R&D Program had not investigated the use of repeaters for surveillance.

The IEC 62320-3 simplex repeater can extend coverage; but its characteristics need closer study by the surveillance community. The simplex repeater has data issues. The IEC repeater is designed to produce a "replica" of the "navigational data" contained in a received message before retransmission. This is done following message conversion rules in the IEC 62320-3 standard. At two places in the IEC standard there is the statement "The repeater station shall not change the data content of the message;" but looking at the retransmitted message from a surveillance perspective. The truth is that the IEC repeater does change the data. The repeater is designed to make specific changes and to discard some information. The IEC repeater also has "operating rules" that are not in the best interest of surveillance and could be detrimental. For the complete discussion, see Appendix sections A.1 and A.1.1.

1.3 Technical Approach

After careful consideration of the standard IEC repeater's design, consideration of desired characteristics in the retransmitted signal, consideration of measurements made of the repeated message at the rebroadcast site, and the desire to extract message information under the worst radio noise conditions, the decision was made to create a "fresh approach" to retransmitting AIS messages. In addition to hardware and firmware upgrades to the SM1680 receivers and SF-162 AtoN-T3 transmitters, the bulk of the implementation of this "fresh approach" is captured in the python based software used to control the transmission and reception of the rebroadcast messages. For an overview of the completed test system, see section "2 Delivered Capability" below.

Concerning the improvement of the repeater radio-link information transferred to the infrastructure, the rebroadcast software manages the construction and scheduling of information placed in the retransmission message. That message can be changed in format and content. Changes may be required as testing is done using weak signals or different types of noise generators. The software is written in python and it is delivered with the equipment. Future changes to the software should be possible as needed, by someone familiar with writing/editing python code.



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The next step in this work is to install the equipment at two laboratory locations and begin comparative testing of the four duplicate message transmission methods: (1) multiple paths, (2) different channels, (3) different slots, and (4) different signal polarizations. Tests will include simultaneous signal transmissions, such as, two signals using the same slot and channel but different polarizations to explore the possibility for improvement of the radio-link bandwidth (e.g., data capacity). Tests using different power levels and “noise” generators will be used to explore the possibilities for repairing corrupted message bits. At this point the effort has been to deliver a working test system and that is complete and documented. The next step is to use the system and make adjustments based on test results and discovered issues.

The rebroadcast method developed for this task has only been designed to support the retransmission of certain single slot AIS messages (1, 2, 3, 4, 18, and 21). If this work goes forward and test results are favorable, other message types can be added to the rebroadcast capability. The rebroadcast structure does not change any bits in the message. The retransmitted message even includes the original message’s CRC. For a complete description of the complete retransmitted message details, see Appendix D.3

This task successfully upgraded the firmware in the SM1680 to study the failure characteristics of AIS messages. In order to test radio-link performance, it is necessary to monitor signals and their failure characteristics as far down into the noise as possible. The upgrades to the SM1680 allows RDC to do this. Current commercial AIS equipment simply does not have this ability. The data output of a commercial AIS receiver is entirely dependent on error free reception of every data-bit contained in the radio packet.

In every AIS receiver, the VHF FM signal to data-bit conversion process includes a validity test. The information used for the validity test is included as data-bits within each AIS radio packet. If the data-bits fail the validity test, the rules that define AIS operation require that the entire AIS message be discarded. In fact, until developed during this work, there was no method for the AIS receiver to provide as output, a message that failed the CRC test. See Appendix E for a description of the VDC-sentence created during this task.

The signal level needed to overcome the radio noise at the surveillance site limits the maximum separation between rebroadcast and surveillance site equipment. Transmission methods are introduced to improve weak signal reception. In addition to power and antenna gain, the delivered capability provides the ability to experiment with four duplicate message transmission options for combating radio noise. The duplicate message methods introduce a signal structure that supports the partial or total recovery of information from noise-corrupted messages. The four options are:

- **Time**, transmit two copies of the same message using different VDL “slots;”
- **Frequency**, simultaneously transmit two copies of the same message on both AIS channels;
- **Antenna polarization**, transmit one copy of a message using vertical polarization and the second copy of the message using horizontal polarization; and
- **Radio path**, simultaneous reception using multiple antenna-receiver combinations.

As the separation between a transmitting AIS unit and a receiving AIS unit increases, the received radio signal becomes weaker. As separation continues, the signal becomes too weak for error free recovery of the radio packet’s data-bits. Signal weakness also occurs when obstructions, such as land (e.g., Alaska Coast Line), begin to block the radio path between the transmitter and receiver. Being able to “repair” received data-bits, or selectively ignore their impact on the message’s information content (partial packet information recovery), would be a significant development in AIS surveillance. As one might conclude, a substantial



amount of information is currently being lost, due to interference and noise causing bit-reception errors. This work delivers upgraded equipment to: support the study of AIS bit errors in noise; and the development and testing of methods for the complete repair of messages or recover of portions of the information contained in damaged messages.

1.4 Task Objectives

The objective of this task was to identify methods that would extend AIS surveillance range and deliver a capability that implemented those methods for further evaluation both in the laboratory and controlled field tests. The capability includes: equipment for installation at a remote rebroadcast site, variable transmitter power and directional antenna options, improved signal processing, and methods to recover information from corrupted messages. The remote rebroadcast site is isolated from alternative forms of communications, such as, a network connection. A complete description of this capabilities components follows in section two (below).

With the AIS radio channels being the only communications link, a metric that drove method development was reduction of the effective bit error rate (BER) of “weak” AIS messages (See Appendix B). The AIS message’s signal strength may be weak due to: the distance and propagation conditions between the transmitter and receiver; obstructions between the transmitter and receiver; and additional radio noise and interfering signals that affect reception at the receiver.

The use of AIS for surveillance also requires that additional information about each AIS message be digitally attached – to improve data integrity and add a level of cyber-security. Therefore, this additional information is obtained and attached at the remote site and transmitted along with each message to the surveillance site. This additional information impacts the system’s bandwidth requirements for the radio link between the remote site and surveillance site. Identification of methods that might improve the bandwidth between the two sites were also studied.

This task has resulted in the delivery of this capability as laboratory equipment that can also be deployed for field tests and proof of concept demonstrations. In addition, it has been delivered in a way that the USCG can modify the system and explore other AIS issues. It is a unique capability that is beyond current AIS standards, and it has no commercial equal.

1.5 Methods Used that are Beyond Current AIS

During the international effort to define AIS, various technical options were decided. These decisions were implemented in the final standard to maximize the mariners safety and with the understanding that: (1) hundreds of AIS units may be interacting in a given area; (2) the need for the AIS units to politely interact with each other using only the two AIS radio channels; and (3) the understanding that corrupted message information is worse than no message information and is intentionally discarded. The AIS message update rate is high and vessel-speed sensitive. While the update rate is high and the message content often redundant, this high update rate is needed to support real-time navigation decisions. It also compensates for the exacting requirement that messages only be delivered when received without errors.

As part of this task, several of these technical decisions were revisited for consideration from the perspective of maritime surveillance; where partial information is acceptable. Also, surveillance does not have the same level of real-time urgency that navigation does. Also, different types of message redundancy



can be used to defeat interference and noise. The exact same message can be transmitted simultaneously or separated in time using different frequencies, slots, and signal polarization. The following is a brief discussion of those options revisited as part of this task.

1.5.1 Repair of messages failing the cyclic redundancy check

AIS units communicate using the marine VHF radio frequencies. Each radio data packet contains one AIS message. The last sixteen bits of an AIS message contain the cyclic redundancy check (CRC). These sixteen bits are mathematically related to the data contained in the message. Every AIS unit is required to perform a mathematical process using the message data and to compare the result to the value of the CRC. If the result of the mathematical process does not equal the CRC, the received message is discarded. There is no provision in commercial AIS equipment to obtain the discarded message. All manufactured marine AIS units incorporate this requirement into their design. By discarding questionable messages, the integrity of AIS as a system is maintained.

In order to study weak AIS signals (messages failing the CRC test), the SM1680 CRC test rules needed to be upgraded beyond detection to also provide some forms of corrupted messages. The purpose of the change is obtain the bits of a “corrupted” message and study the characteristics of message corruption as the signal level weakens with respect to natural and manmade noise. The R&DC owned SM1680 receiver’s firmware was upgraded to detect and provide certain types of corrupted messages. The ability to observe and analyze corrupted messages has resulted in the consideration of several methods that can be used to recover information from a corrupted message.

1.5.2 Elimination of message “stuffing” bits

Each AIS radio data packet consists of a series of binary ones and zeros. The ones and zeros are represented in the radio signal by electronic phase changes; where a phase change indicates a binary data “zero” and no phase change indicates a “one.” In order for an AIS receiver’s electronics to decode a data packet, both the AIS transmitter and AIS receiver follow an international standard. To conform to the international standard, a zero-bit is added to the electronic waveform every time there are five consecutive ones. The result of this process is non-data bit(s) being added to an AIS message. These bits are automatically removed at the receiver; but this process can “go wrong” when a weak signal, radio noise, or interference introduce message data errors during the receiver’s demodulation process. When the AIS signal is weak, a receiver will sometimes incorrectly interpret the electronic waveform and remove the wrong bit – a data-bit rather than a stuffing-bit.

The delivered system is designed to transmit AIS Type 26 messages in such a way that the message does not contain stuffing bits. The upgraded SM1680 receivers are unaffected by this feature; they process all messages regardless of the actual number of stuffing bits in each message.

1.5.3 Use of both vertically and horizontally polarized signals

The IMO intended for AIS to be used in support of collision avoidance. In the IMO installation guidelines, IMO is very specific about the antenna being mounted such that the radiation is vertically polarized. The intention is for the signal to have a uniform strength at all directions from a ship. This is also the customary convention for mobile services.



There is a substantial reduction of a signal's strength when a horizontal polarized antenna is used to receive a vertically polarized signal. This can be used to advantage when communicating between two fixed locations (between a repeater and the surveillance infrastructure) using high gain directional antennas. Tests during this task found the cross-polarization isolation between two directional antennas to be 15 to 17 dB at a separation of 7.5 miles. This amount of signal strength separation could be sufficient to support the simultaneous multiplexing of messages on the same channel, thus doubling the bandwidth (effectively 19,200 baud) of the channel. Figure 3 shows the laboratory equipment used for initial testing.

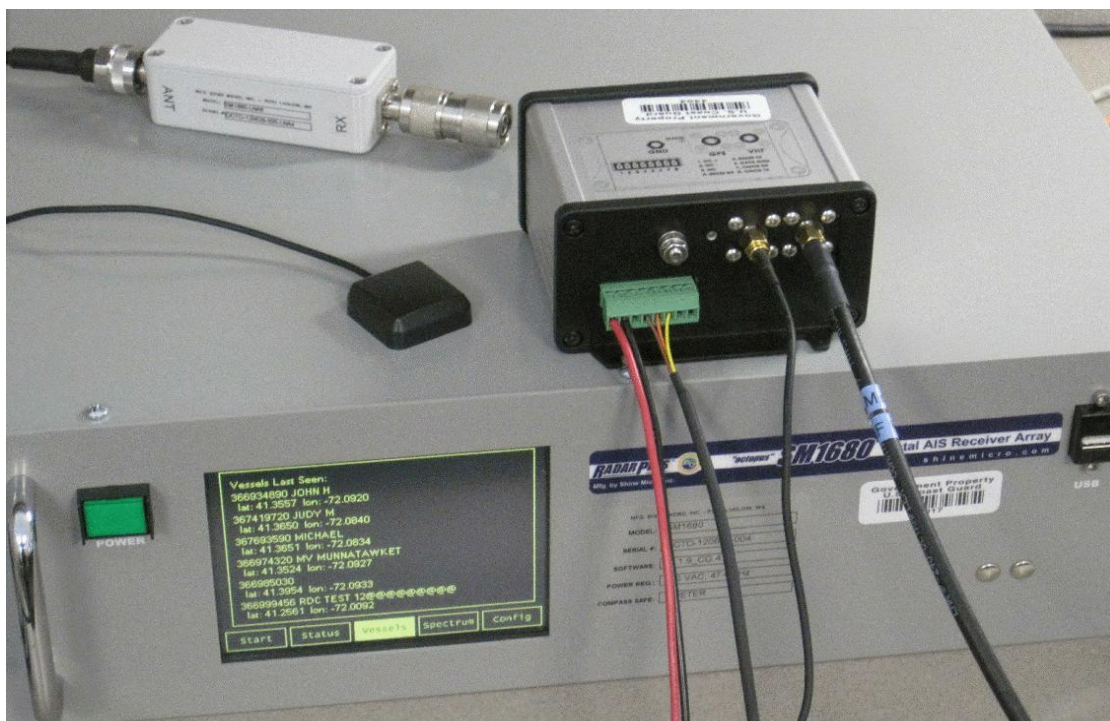


Figure 3. Upgraded Shine Micro SM1680 eight channel AIS receiver (bottom), two channel receiver preamplifier (top left), SF-162 AtoN-T3 transmitter (middle right), and GPS antenna (middle left).

1.5.4 Modified slot use rules

ITU-R M.1371 provides a detailed method to be used to decide when (the slot) a message is transmitted. The underlying principal is “hear and be heard.” In other words, an AIS unit does not transmit simultaneously with another AIS unit, even when the transmission would be on the “other” channel. These rules can be used to advantage by a rebroadcast facility to double available bandwidth without increasing interference or using more slots. Simultaneous transmissions can be made on both channels; because the rebroadcaster is not required to receive all transmissions.

2 DELIVERED CAPABILITY

Today's AIS technology offers two devices that can be used to extend coverage – AIS simplex repeaters and AIS base stations. To different degrees of success, these devices can be used to extend surveillance coverage. However, the methods to extend coverage and improve data integrity addressed in this report introduce capabilities beyond those available from current simplex repeaters and base stations.

2.1 Hardware

Figure 4 (a duplicate of figure ES-1) is a notional diagram of the experimental range extension capability delivered to the USCG RDC.

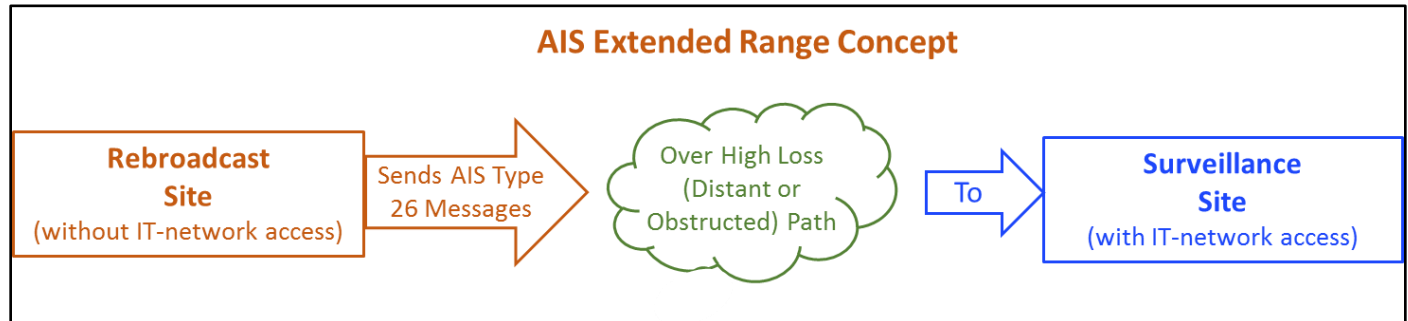


Figure 4. Notional concept of extended range AIS.

The following list the specific equipment used to support testing methods for extending the range of AIS:

- Two (Upgraded) SM1680 Extended Range AIS Receivers: one at the Rebroadcast Site and one at the Surveillance Site.
- Two SM SF162SV-T3 AIS Aids to Navigation (AtoN) transceivers with low power for solar powered applications: both located at the Rebroadcast Site.
- Two computers (Xubuntu OS): one at the Rebroadcast Site (Python) for Assembling the Type 26 message (position reports), Transmission control, and Operation monitoring; the second at the Surveillance Site (Python) for Real-time data monitoring and Data Recording.
- Two Computers (Windows O/S): one for the Rebroadcast site and one at the Surveillance Site both using USCG AIS Miner software [10] to perform real-time signal and data monitor, and AIS signal and data recording.
- Three different Yagi antennas - a 6-element Andrew DB292, a 3-element Yagi, and a 10-element Innovantennas Loop Fed Array (LFA).

Figures 5 and 6 are provided as an expansion of Figure 4. The configuration consists of two equipment groupings. The “Extended Range – Rebroadcast site” equipment (detailed in Figure 5) would be located at some distance from the “Surveillance site” equipment (detailed in Figure 6). The “Surveillance site” would access the MXAK or NAIS using a network connection. An actual surveillance site has additional capabilities that are not part of this range extension experiment, such as, network access and other long-range AIS receivers. Note that the propagation path between the two locations is shown to be relatively high loss. That is, the rebroadcast site is anticipated to be at the periphery of the surveillance site’s nominal long-range reception in an effort to maximize the realized range extension.

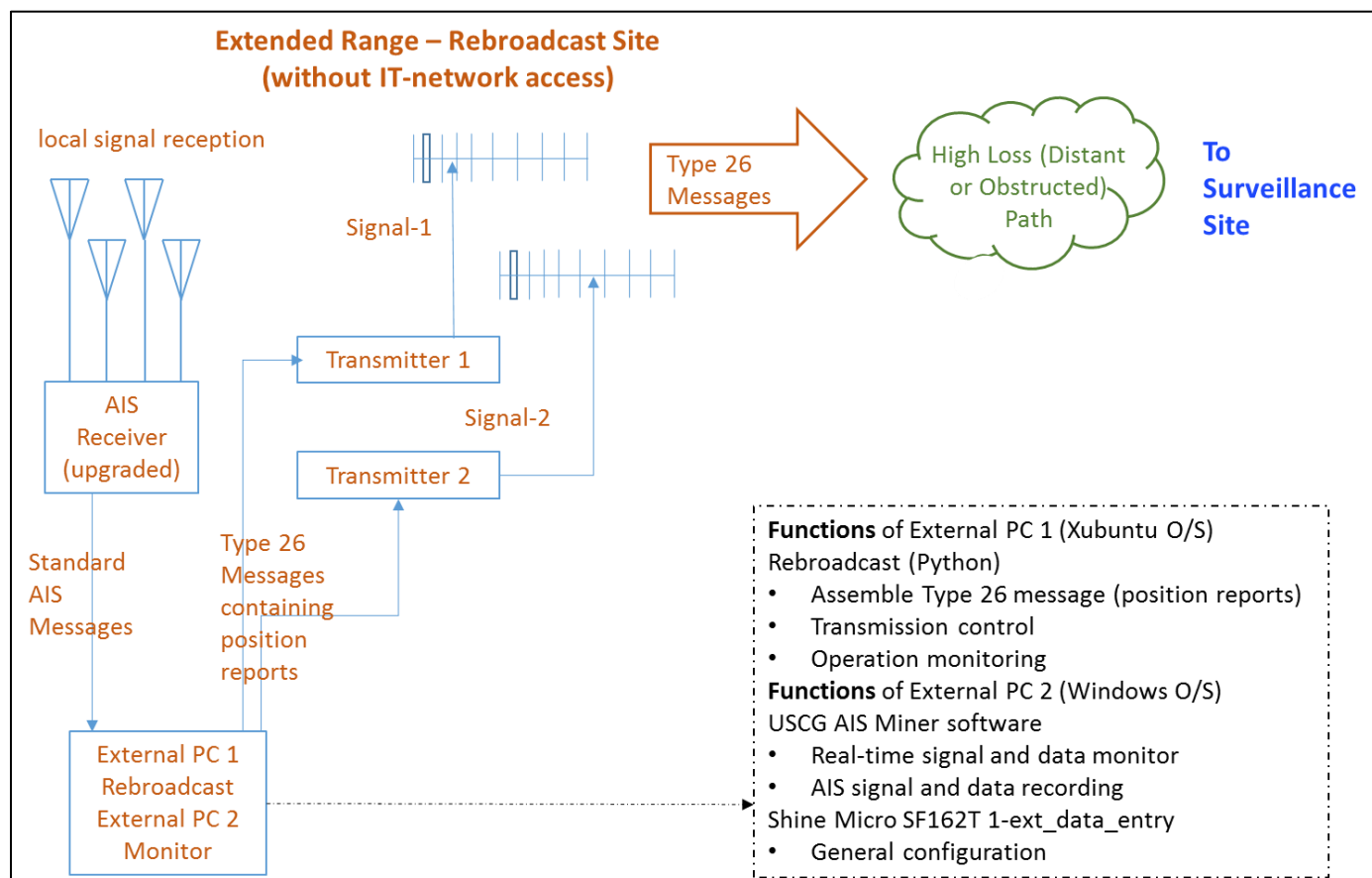


Figure 5. Notional diagram of **Rebroadcast Site** for experimental extended range capability.

The two USCG owned SM1680 receivers (as shown in Figure 5 and Figure 6) received the same upgrades. They are interchangeable. Figures 5 and 6 show only the movement of AIS messages and metadata from the remote area to the surveillance site. While the AIS VHF Data Link (VDL) is bidirectional and other less expensive control options are available, it is premature to speculate on the rebroadcast sites remote control requirements.

Shown in Figure 5 are two transmitters not provided as government provided equipment. Initially the plan was to build prototype transmitters; this was not necessary. Shine Micro was able to meet the needed power level, interface, and transmit characteristics using existing AIS AtoN units. An external computer controls the VDL broadcasts of two independent AtoN transmitters. The use of two transmitters supports evaluation of simultaneous transmissions on one channel using cross polarized antennas, as well as, two separate channels.

The SM1680 at the rebroadcast site also provides measurement information about each AIS message. This information is added to the rebroadcast message data prior to transmitting the complete package of information to the surveillance site.

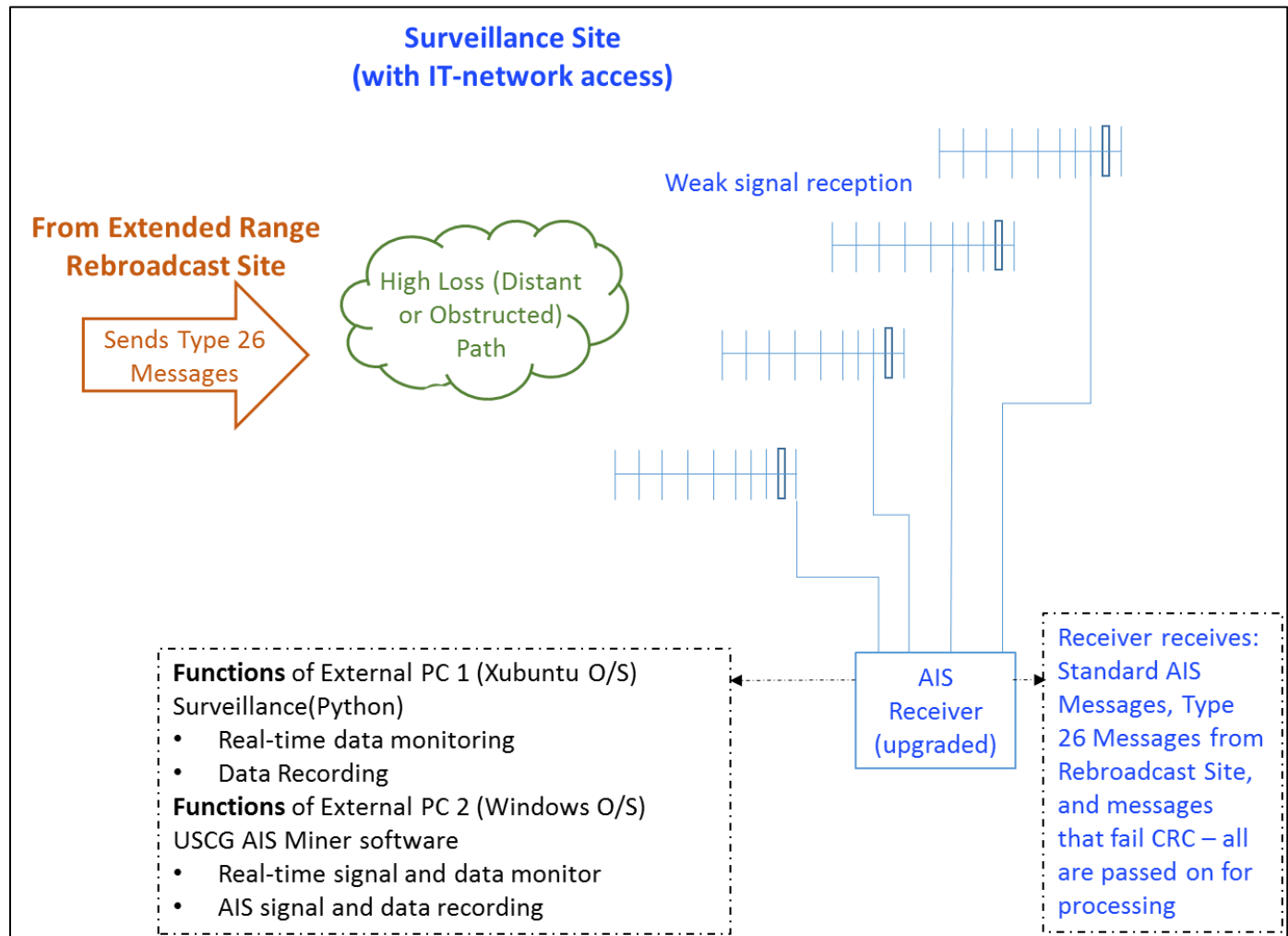


Figure 6. Notional diagram of **Surveillance Site** for experimental extended range capability.

All antenna symbols (in both Figures 5 and 6) are included to indicate their location in this notional diagram. The actual antennas selected, and their configuration, will be decided as the government moves testing from the laboratory into the field.

While the Shine Micro 1680 (SM1680) Extended Range AIS Receiver is commercially available, it is worth noting the history of its development with respect to that additional capabilities that are now implemented within the government owned SM1680s.

The SM1680 was originally developed during 2006 and 2007 under DHS Small Business Innovative Research (SBIR) contract. During the contract, the USCG RDC provided AIS subject matter expert technical support and field test facilities. In 2011, the USCG RDC deployed several SM1680 receivers to demonstrate extended range reception [9] in the Western Gulf of Mexico.

From 2011 to 2013 the government owned SM1680s were modified under contract with Shine Micro to add the ability to digitally record the base-band radio signals used by the SM1680's internal software defined radios (SDR) to receive and demodulate AIS messages. This upgrade included the ability for the SM1680 to use the recorded radio signals in playback mode. With this playback capability and SDR implementation,

the SM1680 provides a “unique in the world” capability to record and then play back the same radio signals – useful for comparing the performance of different design options and methods. This can be used to experiment with changes to the internal SDR and external real-time methods that process the SM1680 output.

Between 2017 and 2018, during this research, the USCG’s SM1680 receivers were again modified under contract with Shine Micro to incorporate operating rules and an experimental sentence structure beyond those of current standards. In particular, the ability to output AIS messages identified during the reception process as corrupted. This ability, as a tool for information recovery, did not previously exist. This capability was possible due to the unique hardware and SDR design of the SM1680; and it is beyond the capabilities of currently available commercial AIS equipment.

In addition to the physical aspects of the prototype, the operating rules need to be established for the automatic selection of AIS messages to be rebroadcast and the scheduling of those rebroadcasts. These rules are expected to evolve depending on the performance results of the new signal processing methods added to the SM1680 and the results of field experimentation. Several rule sets are available as delivered, and they are discussed below.

2.2 Software

Connection and configuration control takes place in the Rebroadcast Software. This software filters received messages, repackages them as the payload of an AIS message 26 along with its metadata and sends them to Transmitter #1 and #2. A screen capture of the connection interface, vessel status, position details by Maritime Mobile Service Identity (MMSI) and data being passed through the connection are shown in Figure 7. It provides a means to monitor and log data based on a specific configuration.



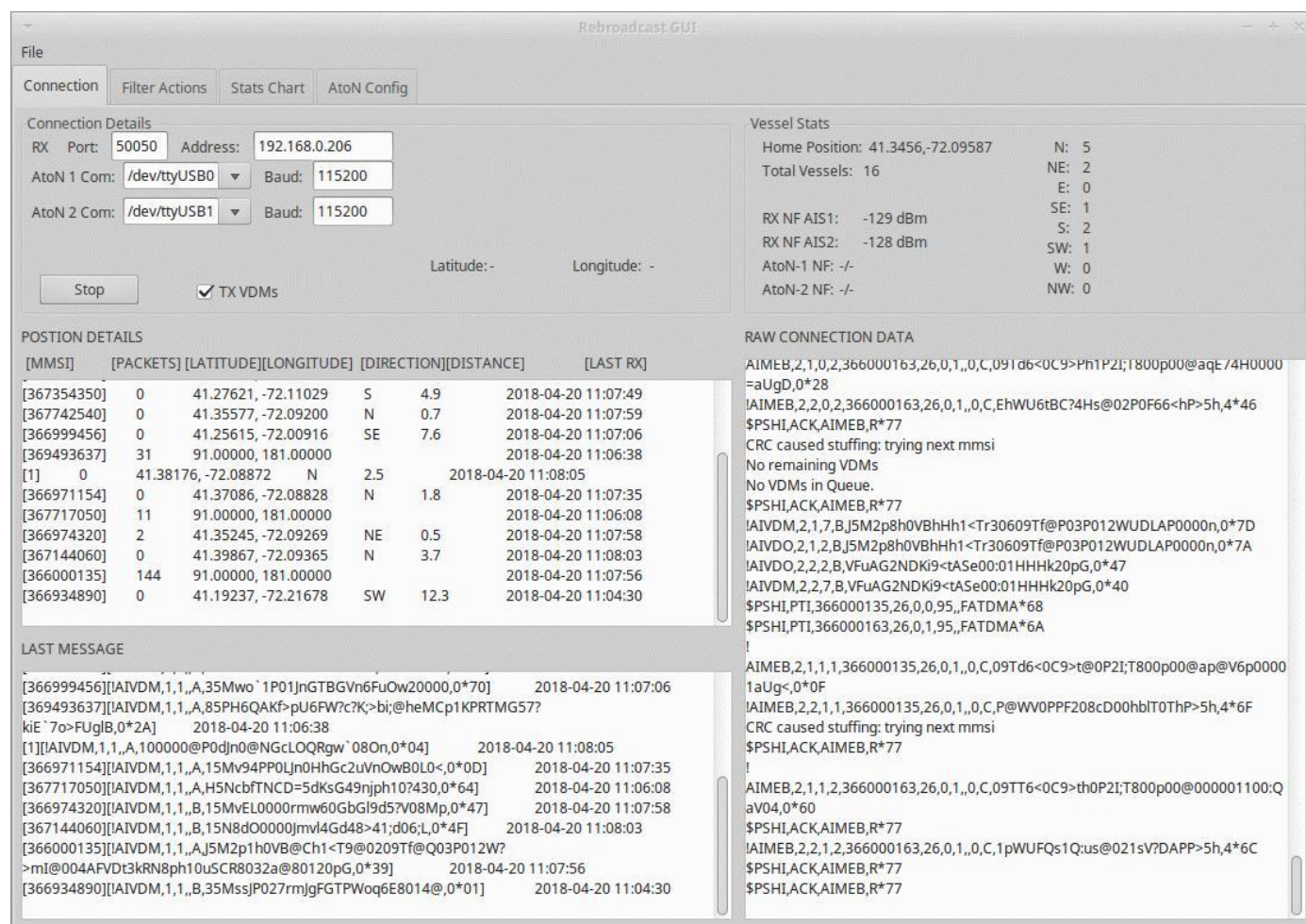


Figure 7. Rebroadcast software control and operation monitoring screen.

2.3 Description of Delivered Capability

Extending AIS surveillance, using only the VHF data link for communications, can be accomplished by deployment of a commercial AIS repeater certified to the IEC 62320-3 standard. However, commercial repeaters are primarily designed to satisfy marine navigation requirements and do not support surveillance requirements. If this is acceptable to the authority interested in extending their surveillance, the deployment focus naturally shifts to cost, power requirements, antenna structures, etc. If the authority is concerned about the authenticity of the “repeated” content or the vulnerability of the surveillance operation to false information, caused by equipment malfunctions or malicious intent, the IEC 62320-3 design requirements need to be reviewed with respect to satisfying an authorities marine surveillance requirements.

In addition to surveillance requirements, there is also the requirement for the authority to maintain the integrity of the VDL in their area of responsibility. To properly execute this responsibility, the authority cannot ignore the impact additional surveillance signals place on the VHF data link and the impact of reduced bandwidth on navigation. The review of the repeater concept in the context of both marine navigation and surveillance requirements should raise questions about the implementation details. The capability this task delivers is intended to provide both hardware options and malleable software that can be adjusted or modified as needed to study issues that go beyond the IEC 62320-3 repeater standard.

Figure 5 is not intended to suggest the final design of a surveillance capable repeater (referred to as a rebroadcaster in this report). It simply diagrams the primary features of the delivered system. It can be rearranged and modified as needed to support investigation of rebroadcast options.

2.3.1 Rebroadcast and surveillance site receivers

The USCG RDC owns the SM1680 receivers used for this task. The SM1680 contains eight software defined AIS radios built with one AIS1 and one AIS2 radio-channel using the same antenna. Four independent antennas can be connected. Two SM1680 receivers were upgraded with additional firmware features as part of this project. The two receivers are interchangeable. The upgraded SM1680 receivers now provide laboratory level features that support testing concepts and options beyond equipment built to AIS standards. Upgrades to the SM1680 receivers include:

- Detection of “Messages Of Interest (MOI)” that do not pass the AIS “CRC test,”
- A new configuration window to control the MOI detection and output, and
- An experimental NMEA 0183 format sentence that delivers failed message content.

The ability to capture and analyze corrupted AIS messages using a high performance receiver is a capability beyond current USCG technology. This capability supports the development and testing of methods that can be used to recover lost AIS information through the use of partial packet data recovery and multiple message correlation. This opens up the possibility for a number of AIS related information studies that may result in higher performance surveillance and communications using lower signal to noise ratio radio links.

Capabilities such as phase measurement are under development for future SM1680 receivers. An AIS message “phase measurement” would be useful to independently confirm the authenticity of the information inside of an AIS position report. The AIS message packet structure and data output sentences developed under this work (See Appendix C) have provisions for adding phase measurements.

2.3.2 AIS message with metadata in one message

The signal measurements of each AIS message received at the remote rebroadcast site (SM1680) are combined with the received message (including metadata described in Appendix C) to create a new message that is rebroadcast to the surveillance site. Provisions are included in this message to add message phase information in the future. In addition to signal measurements and metadata, such as packet signal strength and slot number, phase information could be used to cross check the reported vessel position. The list of metadata includes:

- Separate signal strengths measured by each of the four receivers/antennas of the SM1680,
- Reception channel,
- AIS Frame of reception,
- AIS Slot of reception,
- Number of messages received from MMSI since last rebroadcast,
- The number of different MMSIs received over last eight minutes,
- Channel AIS1 noise floor,
- Channel AIS2 noise floor,



- Time Source,
- Phase difference up to 3 values (provisional), and
- Message CRC.

In addition to these measurements, the rebroadcast site controller has filter settings that can be used to restrict rebroadcast messages to certain “comm states.” The choice of which “comm state” constrained messages are rebroadcast provides different “comm state” data from each vessel’s AIS unit.

Also, a significant upgrade of the SM1680 is the ability to capture for analysis corrupted messages and their metadata (See Appendix E) as received. This opens up future exploration of SDR signal processing methods and external duplicate-message bit repair methods that can be used to better recover the data-bits inside the AIS radio packet. The captured corrupted messages can be used to investigate a variety of multiple message bit-correlation and partial packet recovery methods (future work).

2.3.3 Rebroadcast site controller

AIS messages received by the SM1680 are provided using a network interface to which several external computers can connect. Two computers are connected to the SM1680 network interface. The rebroadcast controller, an Inspiron 14 laptop, operates using a Xubuntu operating system. This computer: gathers AIS messages and message measurements (metadata) from the SM1680; constructs and maintains a queue of messages for rebroadcast; and controls two transmitters that broadcast those messages. The data gathering, management, and transmit control software, “Rebroadcast,” is written in the python language. A second government provided computer can be used to view and record all the SM1680 output using RDC software developed during earlier research, “AISMiner.” See Appendix F for more information about the “Rebroadcast” software.

2.3.4 Rebroadcast site transmitters

Two separate Shine Micro SF-162AtoN-T3 units were upgraded and delivered as part of this task. Their transmitter subsystem is used to rebroadcast messages. The upgrades include:

- Serial interface operation at 115,200 Baud, and
- Support of AIS message 26 format, “Multiple Slot Binary Message with Communications State.”

Each transmitter is independently configured and controlled. The output power of each unit can be externally controlled to operate at 1, 2, 4, 8, 12.5, 16, 20, or 25 watts. Using these two transmitters, the delivered capability can be configured to support simultaneous transmissions on AIS1 and AIS2, or on the same channel using separate directional antennas or cross polarized antennas. All configuration and control of these units is through a serial computer interface.

2.3.5 Rebroadcast site antennas

One antenna is dedicated to each transmitter. Outside the laboratory environment the expectation is that each antenna would be directional to provide signal gain along the path to the surveillance receiver. Figure 8 shows one of the antennas used – a low noise 10-element loop feed array mounted for vertical signal polarization. If the antennas are cross-polarized, that is one antenna is vertically polarized and the second antenna is horizontally polarized, the transmitters could simultaneously transmit using either one or both channels. If



both antennas are polarized the same, the transmitters should only simultaneously transmit when using both channels.



Figure 8. Low noise 10-element loop feed array mounted for vertical signal polarization.

2.3.6 Surveillance site antennas

The ability to use four independent antennas allows the simultaneous observation of the same message using different paths, polarizations, and antenna designs. Antenna gain can significantly extend the distance between the rebroadcast site and surveillance site; however, large antennas may be difficult to install and maintain, in particular, in the Alaskan marine environment. The simultaneous use of different antennas should be a satisfactory way of making final decisions about what antenna design to use for a particular deployment.

2.3.7 Surveillance site receiver monitor

Two computers can connect to the SM1680 network interface. An Inspiron 14 laptop using the Xubuntu operating system can be used to monitor and record received messages. The python based program “SurveillanceGUI” can be used to monitor and record the received messages that fail the CRC test. These

have a dedicated viewing window with the ability to record information to a file. Also, a second government provided computer can be used to view and record all the SM1680 output using the USCG developed “AISMiner” software.

2.3.8 Antenna polarization isolation

Field tests, using a separation of 7.5 miles, successfully demonstrated significant vertical to horizontal cross polarization isolation on the level between 15 to 17 dB using two different designs. This level of isolation supports the idea of further evaluating both vertical and horizontal polarization performance at greater ranges. The USCG use of horizontal polarization when using AIS for communications could improve range and reliability, in particular, in areas with a concentration of AIS units. See Appendix G for more discussion of the antenna tests and potential benefits of using horizontal polarization for special purposes. The results of isolation test also supports the possible simultaneous transmission of control and metadata in orthogonal packet transmissions in the same slot and channel – effectively doubling the point-to-point data capacity of a slot without changing the transmitted data rate. This technique is not expected to support general AIS broadcasting (future work).

The polarization isolation results will impact the design of field tests. For example, the use of horizontal polarization may provide the highest probability of successful message reception at the surveillance site. It will also reduce concerns over interference to standard AIS operation, if the use of higher power (50 to 200 Watts) is necessary.

3 SUMMARY

This effort investigated the feasibility of linking AIS surveillance stations using only the VHF Data Link (VDL) to expand surveillance coverage. This concept is based upon a secondary remote site being installed at a distance from an existing AIS surveillance site. The objective is to have the equipment at the remote site receive AIS messages and make measurements of each message. Based upon a message selection and forwarding rule set, the remote site would forward received messages plus measurements of each of those messages to the surveillance site. The communication of the messages is done using only the AIS VDL. The degree to which this arrangement can expand coverage depends on the VHF communications limitations created by the distance and geography between the two sites. The communications limitation is decided by both the site selection process and the equipment options chosen for both installations. This effort focused on the equipment options.

The inclusion of message measurements is important to help validate the content of each message and to continuously monitor the integrity of the remote site’s operation. Although this effort did not implement encrypted messages in its proof-of-concept implementation, that option remains available in the future to improve the system’s resistance to cyber-attacks without any change in radio-link performance.

This effort did focus on the investigation of options that pursued maximum radio-link performance. If the cost of the remote equipment or the power required for the remote equipment become deployment issues, it is possible to downsize the proof-of-concept equipment and software. There are issues concerning the degree to which message measurements can be sacrificed. Confidence in the rebroadcast message’s contents should be maintained.



The delivered proof-of-concept equipment provides the ability to experiment with four options for overcoming radio noise – options beyond the choice of transmitter power and antenna gain. They are the use of time, frequency, antenna polarization, and radio path. In addition the SM1680 upgrade provides an initial capability to provide in more detail VDL operation where there is a suspicion of integrity issues. The remote site rebroadcast equipment includes two independent transmitters. The two transmitters can be used to transmit duplicate copies of the same information. This supports the simultaneous comparison of different combinations of options. The two transmitters can also be configured to simultaneously rebroadcast two different messages on the same slots or on the same slots and channel using two cross polarized antennas. Both methods support different data repair and bandwidth objectives. The “data repair” objective supports improved reliability of the communications and the “bandwidth” objective to increase the available communications bandwidth while having no detectable increase in VDL use.

This effort demonstrated the ability to capture and analyze corrupted AIS messages using a high performance receiver - a capability beyond standard AIS technology. This capability supports the development and testing of methods that can be used to recover lost AIS information through the use of partial packet data recovery and multiple message correlation. This opens up the possibility for a number of AIS related information studies that may result in higher performance surveillance and communications using lower signal to noise ratio radio links.

Impact of concept on AIS:

Several methods were investigated that improved the performance of the communications link between the two sites while reducing the impact on standard AIS operation. The first was the investigation of horizontal to vertical antenna polarization isolation. Field tests using different directional antennas found the polarization isolation to be about 15 to 17 dB with a separation of 7.5 miles between the sites. This testing needs to be repeated with greater separation between the sites with respect to simultaneous use of both polarizations on the same channel and slot for communications; but the impact on standard AIS can already be summarized. With a 17 dB reduction in effective signal at the remote site, the remote site transmitter operating at 25 Watts and using a horizontally polarized antenna, would appear to have the equivalent signal of a half-Watt by AIS units using vertical polarization. The horizontally polarized communications link would benefit from a 3 dB (25 Watts) improvement over a standard AIS unit (12.5 Watts) while standard AIS operation would only be impacted by the addition of a half-Watt (25 Watts reduced by 17 dB) transmitter. This means that any potential communications interference to AIS navigation messages when using AIS communications messages could be minimized even further by using horizontal polarization.

The rebroadcast process of forwarding messages does not load the VDL with as many rebroadcasts as does an IEC simplex repeater. The rule base for the delivered proof-of-concept capability operates with the rebroadcast rate limited to ten 2-slot messages per minute. This is an aspect of rebroadcasting that needs further investigation during field tests. The requirement for long distance surveillance update rates would also benefit from comment from the surveillance community on the utility and use of the proposed metadata. The results of these discussions are needed to improve the design of the rule set coded into the processing at the rebroadcast site.

Experimentation using the delivered capability:

The delivered proof-of-concept system contains a full set of capabilities to support comparative evaluation of its option combinations both in the “laboratory” and in the field. The best options for a particular geographic relationship between the rebroadcast and surveillance sites will depend on understanding the performance characteristics of each option, or a final decision may require experimentation in the field. The



proper approach is yet to be determined. The performance characteristics of each option and their impact on overall performance are expected to depend on the characteristics of the radio path between the two sites and the noise sources in the vicinity of the surveillance site. For example, under one set of conditions the simultaneous use of the same slot on both channels may provide better performance than the use of different slots on the same channel.

During initial tests of the two systems, it was found that the “laboratory” tests are more easily done with a physical separation of several hundred feet between the rebroadcast site equipment (See Figure 5) and surveillance site equipment (See Figure 6). The experimental results can be unstable and misleading if radio signals are given alternative paths upon which to propagate between the transmitters and surveillance receiver. When testing inside the same space, it is very difficult to establish enough isolation between the two systems to get results that are not biased by spurious signals along alternate radio paths. While more costly in man-hours and time, “laboratory” proximity issues may be difficult to overcome and experimentation may need to be performed during field deployments. The field tests may provide more authentic results than laboratory tests.

4 RECOMMENDATIONS

AIS has now been deployed globally for over a decade. Yet, IMO remains careful in their declaration that AIS is collision avoidance technology – its primary design goal. Over the past decade, AIS has become an integral part of not only the U.S. Maritime’s cyber environment; it is an integral part of the global cyber environment. Like GPS, the AIS information is routinely used to make critical navigational decisions. Blind dependency on AIS information may not be safe. AIS was developed and deployed during a time when cybersecurity was not an issue or requirement. Its requirements were drafted and primary standards completed prior to the events of 9/11. Beginning today, it would take a decade to effectively add cybersecurity to AIS. It is important to now begin an international discussion on the requirements for the next generation of AIS – “AIS 2.0.” As with the development of the initial AIS standards, perhaps the USCG should take a lead position in providing technical and operational input to the international process.

This task has delivered a capability that goes beyond current AIS technology. This capability enables more detailed study of VDL activity and the nature of message corruption; and it transitions the analysis of the AIS radio-link to software defined radio methods. This enables the investigation of cybersecurity threats and the effectiveness of countermeasures using both defensive and offensive methods. This information will be important in defining the next generation of AIS.

The topics recommended for further consideration and action are:

- 4.1 AIS 2.0: Initiate and support an international review of AIS collision avoidance and cybersecurity issues to launch the effort to define the technical requirements for the next generation of AIS technology. (This work begins inside the committees and working groups of IMO, IALA, and IEC.)
- 4.2 Establish a working group and document surveillance requirements for an AIS shore infrastructure. (This working group should include the organizations who currently use, or react to, the surveillance information and those who operate surveillance networks – USCG, USACE, and MXAK.)
- 4.3 Continue AIS radio-link research into performance enhancement methods, supporting all other topics recommended in this section, and that may fundamentally and positively impact all uses of AIS. (RDC)



- 4.4 Initiate AIS VDL integrity monitoring research. (RDC working with issues provided by operators of shore surveillance infrastructures – NAIS, USACE, and MXAK.)
- 4.5 Initiate exploration of “AIS-friendly” methods that enhance the use of AIS for communications. (RDC working with C4IT)
- 4.6 Investigate defensive and offensive real-time cybersecurity methods and countermeasures for use with both current AIS technology and the next generation of AIS. (RDC working with USCG representatives to IMO, IALA, and IEC; also, linked to topic “4.4” effort; and following DHS direction to defend critical maritime infrastructure.)

4.1 AIS 2.0

The formal process that created the current requirements for AIS equipment began in 1998; but the background research began years earlier. The primary USCG interest in AIS was as a VTS surveillance tool that would replace the need for extensive and expensive radar coverage of the lower Mississippi River for the New Orleans VTS. An important secondary interest was concluding the AIS equipment standards quickly – Class A standards were completed by the summer of 2001. Other countries also needed AIS for their VTS services, and there was significant cooperation in moving the standards along.

During development, within the AIS committees there were questions about AIS being treated as a component of GMDSS. That was openly discouraged; because it would slow down the process and complicate the requirements and adoption of the final equipment standards. Subsequent to 9/11, the openness of AIS technology was debated; but because the standards were already agreed at the international level, the notion of making eleventh hour changes was discouraged and speeding deployment encouraged. Since the deployment of AIS, global security concerns about the system have grown and operational use has quietly incorporated GMDSS functionality – i.e., AIS SART and SAR aircraft AIS units.

Today, initiatives such as the DHS “Cybersecurity Strategy” (May 15, 2018) [5] create new national objectives that should serve to support a USCG suggestion of an international effort to upgrade AIS. Added to the original list of requirements are now cybersecurity features that protect the U.S. Maritime’s cyber environment and GMDSS. The combination of cybersecurity and GMDSS issues, backward compatibility with current AIS, and the scarcity of supporting research will slow the completion of the AIS 2.0 upgrade requirements, decisions, and standards. If this initiative were to begin in 2018, expect that it will take a decade before a significant number of AIS 2.0 units appear in the field. In addition to the shipboard units, expect that parallel upgrades to the shore surveillance infrastructure will be needed to realize the full cybersecurity and GMDSS benefits from AIS 2.0.

4.2 AIS Surveillance Requirements

Appendix section A.2 reviews and discusses the repeater rules that IEC defined for how an AIS repeater operates and the information that it retransmits. The IEC AIS repeater does meet the navigational needs of the mariner; but it turns out that navigational requirements are not surveillance requirements. This quickly became obvious when a “repeater” designed for surveillance became the objective. The bottom line of the discussion is that the current IEC repeater is not designed to appropriately satisfy the needs of an AIS surveillance infrastructure.



Further searching for surveillance requirements did not result in a reference that clearly describes AIS surveillance needs – with respect to AIS message content and validity or detection of operational VDL issues. This is probably due to the resignation that the AIS is designed to support navigation and expending an effort to catalog surveillance specific requirements outside the current design is a futile exercise – perhaps, until now.

A major issue with AIS today is that, without radar backup, it operates without giving the mariner a safety net. As a safety issue, this is magnified as mariners operate in congested areas – ports, rivers, and coastal waterways. The only “reliable” source of an AIS-safety warning might be an AIS surveillance system that detects an issue with AIS operations. So, who might be the authority and how would it work?

This future work could help improve real time monitoring of AIS to detect and defend the maritime infrastructure and Marine Transportation System (MTS) from possible malicious attacks on AIS.

Expect an honest review of AIS surveillance requirements to produce a significant level of new requirements relative to the current use of AIS for surveillance. Current AIS navigation-requirements do not align well with the DHS “Cybersecurity Strategy” (May 15, 2018) and USCG “Cyber Strategy” (June 2015) objectives. The AIS surveillance infrastructure should be the mechanism for discharging a responsibility articulated by IMO. IMO expects the authorities to ensure the integrity of the AIS VDL. Because USCG operations get the call when things go wrong, it seems reasonable that USCG operations would want someone “working the issues;” so that ultimately they do not need to get “the” call.

There is a need to have ready a vetted list of AIS surveillance requirements to support technical decisions about AIS equipment capabilities: both in the context of the current definition of AIS and design upgrades to the current infrastructure; and to support discussions about the next generation of AIS equipment capabilities. In particular, AIS requirements need an upgrade with respect to advanced Global Maritime Distress Safety System (GMDSS) and cybersecurity responsibilities.

4.3 Radio-link Enhancement

The objective of this task’s efforts was to deliver methods and capabilities that enhance the performance of the AIS VDL radio-link between repeater sites and the existing AIS infrastructure. That part is now complete with the delivery of the equipment, software, and this report. Future work is intended to use the delivered capabilities both in the laboratory and in the field to assess the different methods and their combinations to determine their benefits. The work to date included initial testing done to confirm equipment and software functionality or to confirm a method. In addition, the same capability can be used to study other AIS related issues, that is, support other topics described in this section’s list of recommendations. Continued work on the topic of radio-link enhancement includes the following:

- Transmit duplicate Type 26 Extended Range messages using time, frequency, polarization, and path (TFPP) multiplexing through high attenuation and/or high noise paths and use the received corrupted versions of a message to develop and evaluate methods that repair that AIS message; or accurately recover portions of the message. (Key notions: bit repair software, two CRC validation, partial packet information recovery)
- Upgrade existing RDC AIS analysis software, “AISMiner,” to support the additional NMEA-like sentences invented to support this work. (Key issues: Type 26 Extended Range message; PRDC,VDC corrupted AIS message.)



- Evaluate and rank the costs and benefits of the options: power; antenna gain; and duplicate messages via frequency, time, path, and polarization.
- Evaluate and upgrade control and data collection software written using the Python language - refine rebroadcast rules and requirements.
- Further test the limits of cross-polarization for doubling the data bandwidth of an AIS “slot.” (Key notions: long distance field tests; land and water; horizontal and vertical polarization fading differences, productive TFPP combinations.)
- Assemble a rebroadcaster site survey package. (Key notions: method/software development, minimum size/power capability, survey message.)
- Minimum power-consumption rebroadcaster. (Key notions: limited site resources, use buoy power system, different surveillance requirements.)
- Demonstrate signal phase measurements. (Key notions: evaluate SM1680 phase measurement upgrade, investigate AIS message validation methods.)
- Formulation of a recommendation concerning those things to be considered for a rebroadcaster standard and support AIS 2.0 activities.
- Assess methods for overcoming signal “barriers” – see following note. (Key notions: offshore Gulf of Mexico surveillance, protect rebroadcast slots with FATDMA.)

Note: Though this work is intended to study VDL enhancement to overcome physical signal blockage (islands, hills, mountains, and horizon [distance]), it may be more valuable in high AIS signal congestion areas where distant surveillance is “blocked” by AIS signals where there is a high vessel concentration. Using a rebroadcaster and FATDMA slot reservations, it may be possible for distant AIS messages to be conveyed to the infrastructure. This could serve both surveillance and communications (Key notions: Gulf of Mexico surveillance; extend STEDS service range and improve reliability).

4.4 VDL Integrity Monitoring

As reliance on AIS information increases, more attention will need to be given to automated methods that detect VDL issues, information errors, and equipment malfunctions. IMO MSC.1/Circ1252 provides guidelines for annual AIS testing, and some countries, such as the UK, have published their own custom guidelines. However, these guidelines do not deal with the real-time VDL issues, such as, equipment malfunctions and malicious intent. Only continuous automated processes have the potential for providing the needed level of monitoring, and the AIS industry will not develop and deliver solutions without USCG involvement and funding. In particular, the USCG needs to determine: the specific monitoring requirements; and the testing methods needed to declare success.

The operational impact of this work:

- Have USCG AIS processes in place and continuously delivering their services to those USCG operations that are reliant on dependable information from AIS sources.
- Routine detection and resolution of VDL and equipment issues – both mariners and government.
- Resource conservation realized from informed decisions.
- Improved preemptive warnings of potential maritime distress conditions.
- Alerts to attempts to use AIS inappropriately or to cause injury and damage.



The SM1680 upgrade delivered under the current task, which is primarily designed to detect and provide corrupted Type 26 extended range messages, was implemented to allow the study of any AIS message type. Although unable to take on all aspects of VDL integrity monitoring, the SM1680 upgrade does provide an initial capability to study in more detail VDL operation where there is a suspicion of integrity issues.

4.5 AIS for Communications

AIS equipment supports a limited communications and text messaging capability. It is limited by design to protect the integrity of the AIS service. The current task found two methods that could improve the range and reliability of the current AIS communications methods. These two methods can be implemented while continuing to protect AIS service integrity. Recommendation 4.3 “Radio-link Enhancements” (above) introduced a third method using a rebroadcaster to improve communications; but the methods studied under this recommendation do not require a rebroadcaster.

The first method would change the transmitted “communications” signals from vertical to horizontal polarization. During preliminary tests of point-to-point communications using high gain antennas, the polarization isolation was found to be 17 dB. If this isolation also exists between horizontal and vertical polarization between the AIS mobile-to-mobile radio-links, communications using horizontal polarization would benefit. The general characterization of cross-polarization isolation among shipboard AIS units requires more study.

The second method would add a second transmitter to the USCG AIS units. The purpose would be to simultaneously transmit on both AIS channels. The transmitted message could be either the same message on both channels to improve reliability of communications or different messages on each channel to effectively double the information bandwidth. The needed equipment modifications, software changes, and interface software requires development, fabrication, and more study. This approach also requires the use of messages that make SOTDMA or ITDMA slot reservations to be fully effective.

The equipment under the current task “Radio-link Enhancements” was delivered with the basic hardware building blocks needed to begin testing this concept before any modifications to USCG AIS units – some software development is required.

4.6 AIS Cybersecurity Methods and Countermeasures

AIS is perceived as an open and therefore vulnerable technology. This is reinforced by the design of existing commercial AIS equipment conforming to “minimum” IEC recommendations. The AIS concept has been in practice for over a decade and has been proven to be sound, however, the current AIS design did not consider cyber security issues.

Research into the next generation of AIS needs to consider both defensive and offensive cybersecurity methods as part of the “future minimum” AIS recommendation. As with the current generation of AIS equipment, not all equipment should have the same cybersecurity capabilities. Like AIS base stations, the competent authorities would have the complete set. There are known software defined radio methods that can be added to AIS equipment to improve confidence in the authenticity of an AIS signal and that signals information content. These methods need to be further developed and demonstrated prior to inclusion in the next cycle of AIS standard upgrades.

Researching Technology Improvements for AIS

During the review of AIS repeater operating rules and functions, it became apparent the repeater is designed to navigation requirements. What seems to be missing from the “discussion” is a good statement of “AIS surveillance requirements” - which would include cybersecurity issues. Until Recommendation 4.2, “AIS surveillance requirements,” is undertaken, this effort should include the involvement of USCG operations (and other interested parties) to develop a list of AIS surveillance requirements and questions. For example, does “surveillance” include warnings to AIS participants when VDL integrity is under attack or a particular MMSI is “suspicious”? Or, how aggressively should the USCG attempt to silence an offending AIS signal source?

The operational impact of a proactive cybersecurity capability would: (1) Improve confidence when making operational (for example, SAR) decisions based upon AIS information sources; (2) Reduce the amount of resources wasted on issues or events erroneously initiated by equipment malfunctions or individuals with malicious intent; and (3) Identify AIS units that represent a threat to operations, and perhaps the ability for USCG to take operational countermeasures.

The AIS radio signal has unique “laws-of-physics” characteristics. For example, they are limited to a geographic area. These characteristics and geographic limitations can be collectively thought of as a “fingerprint.” If an AIS receiver only provides the information inside the AIS signal, there can be reasonable doubt about its validity. If the AIS receiver also provides physical measurements of the AIS signal along with the signals information content, the measurements may be used to independently corroborate some of the information content. When the signal measurements and signal content “agree,” there is higher confidence that the source is valid and equipment working as expected; but, when they do not agree, the information content should be handled differently and perhaps some “challenge” action taken.

Software defined radio technology is used to construct AIS equipment. This fabrication method can incorporate signal-processing options that add information about each AIS signal; but this information is secondary to the primary AIS functionality. Access to AIS signal measurements could be of significant value to authorities facing cybersecurity issues. These methods are not currently defined or required by existing AIS equipment standards.

The two upgraded SM1680 AIS receivers used during the current task have the ability to deliver more information about VDL performance than standard AIS receivers. They also have the ability to record and replay the AIS channels signal content for the re-study of VDL events using different reception options. This is a new and important analytic capability and should be studied in greater detail, in particular, with respect to VDL performance issues and where there are issues concerning anomalous signal and denial of service message activity. The upgraded SM1680 receivers are unique. NAIS does not have this capability, and it is not commercially available in other equipment.

This work is expected to produce suggestions for offensive cybersecurity methods that could be the subject of future research.



5 REFERENCES

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APPENDIX A. REPEATER VS REBROADCASTER REQUIREMENTS

A.1 AIS Equipment - Basic Design Background

IEC standards define the minimum performance requirements for an AIS device. Each type of AIS device has a separate standard. Each standard contains a series of electronic, logical, and operational tests the device must satisfy. Each AIS equipment design is patterned after a common basic model (See Figure A-1).

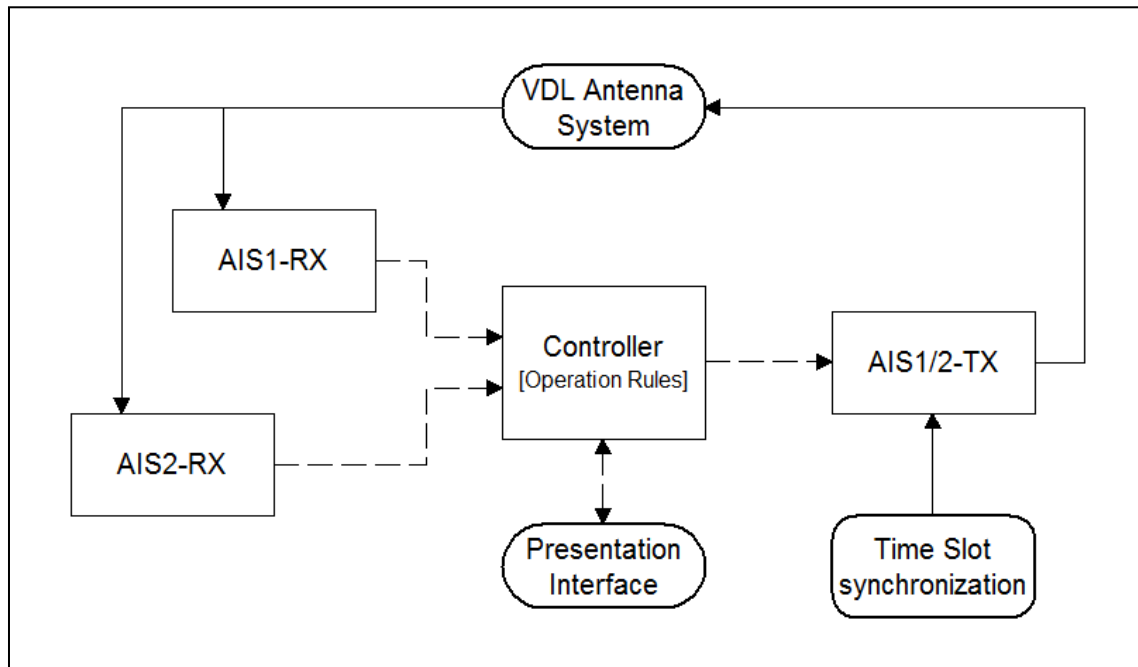


Figure A-1. Notional AIS device.

Inside an AIS device are two receivers, one dedicated to each AIS channel. Each receiver simultaneously and constantly processes the radio energy from the antenna system to detect and demodulate AIS messages. The controller processes the messages and the information they contain, following the particular device's operating rules as defined by IEC. The controller is a microprocessor using software that provides configuration options. The specific options depend on the AIS purpose of the device. The controller also gathers information and prepares AIS messages for broadcast; and it provides control of the transmissions on either of the two AIS channels (AIS1 or AIS2). A time slot synchronization process, that normally uses GPS as its timing source, controls final timing details of the transmitters broadcast. The controller also manages digital information that is accepted or delivered by way of the presentation interface (PI) – the digital communications avenue to other local electronic devices.

The controller's software requirements are defined in the various IEC AIS device standards. The radio signal and data content of received and transmitted signals are defined in the ITU-R M.1371 standard that defines AIS technology, in general. The local data interface is called the Presentation Interface (or PI) and for shipboard equipment it is an electrical and digital data connection primarily described in the National Marine Electronic Association's (NMEA) 0183 and 2000 standards. A common electrical interface for

shore based AIS equipment, such as the SM1680 receiver, is a RJ45 Ethernet port with a fixed Internet Protocol (IP) address; with the data format as described in NMEA 0183.

One significant design change suggested in this report is for the rebroadcaster (surveillance repeater) to contain two, four, or maybe more transmitters and a controller capable of accepting an increased computational load. More than four transmitters may be needed if the rebroadcaster is part of a chain of rebroadcast sites (A notion for consideration in future work.). The need for two or more transmitters is required to support the simultaneous transmission of messages using different channels and antennas. During this phase of the research two transmitters are used to support initial testing of the comparative performance between different option pairings and simultaneous transmission performance. The objective of simultaneous transmissions is two-fold: (1) to increase the effective communications bandwidth available for sending messages to the surveillance site; and (2) to experiment with duplicate message reception and data-bit correction methods to combat radio noise when the radio-link between the rebroadcast site and surveillance site is marginal.

A.2 Discussion of Simplex Repeater versus Rebroadcaster Functional Requirements

The device defined by IEC to extend AIS signal range is called a “simplex repeater.” Its design conforms to the notional design shown in Figure A-1. A simplex repeater extends signal range by: (1) decoding AIS messages of various signal strengths and, (2) after a brief delay, retransmitting a facsimile of those messages on the same channel upon which each message was received. The controller’s message selection, or filtering, is based upon configuration options selected during installation of the repeater. The message retransmission is designed and scheduled such that it should not disrupt the operation of the VDL or cause confusion on a mariner’s navigational display.

The minimum functional and performance requirements for standard AIS repeaters are described in IEC 62320-3 sections four and five. In summary, the objectives of the IEC repeater’s store-and-forward design are:

1. Extend AIS reception range to provide information that improves mariner’s navigation decisions,
2. Automatically retransmit AIS messages with minimum alteration of message data,
3. Process messages promptly, so as to not disrupt “same message” information received directly, and
4. Cause minimum disruption of the standard AIS VDL operation and “slot-reservation” process.

In order to cause minimum disruption of the VDL, IEC chose to significantly change the use of the retransmitted message’s “communications state” data field. This is discussed further in §A.2.2, below. The IEC repeater is also required to quickly process and retransmit messages. This is good for meeting navigational requirements; but may place unreasonable power consumption requirements on a deployment to a remote site. This can be an issue for an authority desiring to deploy a repeater in remote areas for surveillance. For example, the MXAK often faces reliable power issues for its equipment at remote sites.

Unlike the internationally vetted IEC simplex repeater requirements, the rebroadcaster’s hardware and retransmission rules are currently only conceptual. This report provides an introduction to features that could become rebroadcaster requirements after assessing the benefits of field-tested technical options and discussing operational needs and cost-benefit issues with the surveillance community. In final form the rebroadcaster requirements could be formulated as a mix that satisfies both surveillance and navigational needs. This would enable an authority to customize a rebroadcaster’s operation to meet specific needs without deployment of multiple repeater-types.



A.2.1 Rebroadcaster requirements

This sub-section and the four following sub-sections (§A.2.2 to §A.2.5) discuss requirements that should be considered for an AIS repeater designed to support the surveillance function of an existing AIS shore based infrastructure:

- §A.2.1 Guiding objectives and discussion of information bandwidth enhancement,
- §A.2.2 Surveillance information lost when using an IEC simplex AIS repeater,
- §A.2.3 Message repeating (repeater slot reservations)
- §A.2.4 Message retransmission scheduling, and
- §A.2.5 Message selection for retransmission.

The overall focus of this report concentrates on improving the performance of the radio-link; but the final list of specific rebroadcaster requirements should also consider information flowing from the shore infrastructure to the mariner – such as, safety information broadcasts. Bi-directional improvement of the radio-link should easily follow from the work recommended in §4 of this report. The following four sub-sections focus on maritime surveillance issues.

Politeness is a basic design principle that needs to be respected by any non-navigational messaging using the AIS channels. Here, politeness is respect for both established AIS rules and radio engineering methods that minimize any operational impact on standard AIS use of the VDL. Politeness is one reason for seeking methods that improve the effective bandwidth of the AIS channels' time slots.

This sub-section contrasts the “objectives” of the simplex repeater (See §A.2 above.) with a similar objectives list for a rebroadcaster (maritime surveillance, broadcast safety information, etc.); and expands on the notion of simultaneous retransmissions. The overall objectives of the proposed rebroadcast repeater design could be:

1. Extend AIS reception range to provide information that enhances the performance of a shore infrastructure – maritime surveillance and communications,
2. Automatically retransmit AIS messages with no alteration of message content (See Appendix D) along with measurements of the original signal (See Appendix C) that contained the message,
3. Process messages for retransmission based upon the infrastructure preferences, and
4. Cause minimum disruption of the standard AIS VDL operation and “slot-reservation” process.

In order to cause minimum disruption of the VDL, this study developed a data payload (combination of retransmitted message with its metadata) for encapsulation within the existing AIS Message Type 26. Essentially, the use of the Type 26 message transforms a navigation message to a communications message. The payload is described in detail in Appendix D. The result from using the Type 26 message is that standard AIS units will essentially ignore the content of the message (thus not confusing their navigation displays); but will use the Type 26 message slot reservation information provided in the “communications state” of the message. AIS units receiving the Type 26 message will decode the communications state and not transmit on either channel during the reserved time slots. Thus maintaining orderly use of the VDL.

In general, standard AIS units will not use either the AIS1 or AIS2 channels for any time slots reserved by another AIS unit, in particular, in a low traffic area. A little known fact about AIS slot usage is that AIS units contains logic that attempts to avoid transmitting on either of the AIS channels during the time another AIS unit is transmitting. The reason for this is that the unit's receivers “go deaf” when the unit is



transmitting. In order to not miss a message that could be important, the rules of AIS have units not transmitting on either channel during the time slots of a known scheduled transmissions by other units.

This AIS feature can be exploited by a rebroadcast repeater that has multiple transmitters. The rebroadcast controller can schedule two simultaneous transmissions, one on AIS1 and a second on AIS2, thus doubling the effective AIS bandwidth of the radio-link between it and the surveillance receiver. In addition to using both channels during the same slot, there are two other “doubling” methods that require further field tests. The first is using the isolation between an antenna’s vertical and horizontal polarization. The second is communication with a third site located in a direction outside the main beam pattern of the antenna pointed toward the surveillance receiver – for example, a second shore surveillance site or another rebroadcast site. More detail about cross-polarization and very directive (or low noise) antennas is provided in Appendix G. If all these methods prove effective over distant separation paths, the effective bandwidth of a slot could be increased eight times, and to take full advantage, this would require the rebroadcast repeater to use eight separate transmitters.

The following four sub-sections discuss particular functional requirements of the IEC simplex repeater in the context of their relationship to a rebroadcaster designed to support surveillance. The contrast provides some insight into the awkwardness of using a simplex repeater for surveillance in a world sensitive to cybersecurity issues.

A.2.2 IEC simplex repeater – Lost information

Surveillance using AIS has a variety of requirements that are unique for every authority, depending on their mission requirements. However those requirements are defined, one principle is common; and it is, “Do not arbitrarily discard information.” The IEC simplex repeater, by design, does discard information important for surveillance. In addition, simply “disabling” the discarding process is not a “fix” acceptable by the IEC repeater design. The information is being discarded for the very important purpose of maintaining the integrity of the VDL and to minimize VDL disruption by repeated messages. An acceptable “fix” requires a fundamental redesign of the retransmission paradigm (i.e., a new standard); and that is exactly what this investigation of “rebroadcaster-requirements” is addressing.

During the processing of a repeater message an IEC 62320-3 repeater discards some information that is important for a surveillance network. That information are:

- Information inside the message’s “communications state.”
- Pending messages in the transmit-queue will “time-out” even if a replacement message is not added to the queue.

The IEC62320-3 repeater standard requires some portions of an SOTDMA message be changed prior to the message’s retransmission. They are:

- “Synch state” is changed to the synch state of the repeater,
- “Slot time out” is set to “zero,” and
- “Slot offset” is set to “zero.”

These requirements cause information of surveillance interest to be lost before the message’s retransmission. The details are as follows.



Researching Technology Improvements for AIS

Synch state: This indicates the timing source used to transmit the original message. This information is important for: (1) monitoring GPS performance (for example, GPS signal interference or blockage), and (2) detecting a malfunction of the AIS unit's time reference sub-system. If GPS is the position source for the AIS unit (which is normally the case), this information can also be a leading indicator that the position reported in the message may not be correct.

Slot time-out: The SOTDMA communications state contains a 14-bit sub-message. The information in the fourteen bits is linked to the slot time-out value, a value from zero to three. The IEC repeater standard requires that the slot time-out of a retransmitted message always be zero regardless of what it was in the original message. This means that information items "1," "2," and "3" below are permanently deleted from a repeater's retransmitted "SOTDMA" messages. The lost information includes the following:

1. The number of other AIS units currently being received (slot time-out of 3, 5, or 7),
2. The slot number in which the message is transmitted (slot time-out of 2, 4, or 6),
3. The UTC hour and minute of the message transmission (slot time-out of 1), or
4. Information about the change of this message's slot reservation (slot time-out of 0).

Slot offset: The offset indicates the time in the next minute being reserved by the AIS unit during which another message will be transmitted. When this reservation violates an already existing reservation for the same slot (on either channel) this provides some indication of an AIS unit's ability to receive other AIS signals. This can be an indication of a failure of the AIS unit's receiver sub-system or that the origin of the message may not be originating from the position it is transmitting in the message!

An IEC simplex repeater also has several "operating rules" that are not in the best interest of surveillance; and may actually be detrimental. The following are a list of required features from IEC 62320-3 that may be detrimental for surveillance:

- The maximum delay of the retransmission shall be within 9 s [s = seconds] of reception in order to ensure one minute interval UTC time stamp in a position report that has undergone multiple repetitions. If RATDMA is used to transmit a message, the received message can be held for maximum 4 s and 10 slots.
- With the exception of AIS-SART position reports, messages containing a time stamp older than 30 s shall not be repeated.
- The repeater station shall be capable of retransmission of a message within 10 slots of reception of that received message.
- Retransmission (repeat) shall be performed on the same channel in which the original message was received by the repeater station.
- Each time a received message is processed by the repeater station, the repeat indicator value shall, at least, be incremented by one (+1) before retransmitting the message.
- If the received repeat indicator equals 3, the relevant message shall not be retransmitted.

The following two sections present examples of requirement differences between simplex (navigation) repeaters and (surveillance) rebroadcasters.



A.2.3 Message repeating (repeater slot reservations)

This sub-section presents the current method by which an IEC simplex repeater uses VDL slots and discusses how a rebroadcast repeater should use VDL slots. An important point to appreciate is that a simplex repeater is inside the community of AIS units it affects most and the retransmitted messages are intended for all AIS units within range. The rebroadcast repeater is distant from the intended reception site. The AIS units around the rebroadcast repeater are different than the AIS units around the surveillance site. System level measures need to be taken to reserve (and protect) the slots being used for point-to-point communications between the two sites. Maintaining a fixed and unchanging set of slots for point-to-point communications is the most polite of ways to use the VDL. This approach introduces the minimum disruption of AIS units' frame maps and reduces potential radio-link interference.

Taken from: IEC 62320-3: §4.1.2.2 – Message by message repeating:

“Each received message that shall be repeated is internally allocated for transmission using RATDMA, ITDMA, or FATDMA” [Random Access Time Division Multiple Access, Incremental Time Division Multiple, or Fixed Access Time Division Multiple Access] “as supported and configured.”

Potential Rebroadcaster requirement for message by message rebroadcasting.

Each rebroadcast shall be internally allocated for transmission using SOTDMA or ITDMA as supported and configured.

Discussion

The rebroadcast station's transmissions are intended for a distant facility; most probably outside the “local community of AIS units. Because of the expected distance separation, the VDL frame map at the rebroadcast station will be different than the frame map of VDL activity surrounding the surveillance station. In order to improve reception performance, the surveillance station may reserve the slots configured at the rebroadcast site using message AIS message “Type 20” FATDMA slot reservations; this is an operational option. In the area of the rebroadcast station, the rebroadcaster's transmissions should be in harmony with the local VDL community.

The configuration of the rebroadcast site should include the slots it should use. This will serve several purposes: (1) Limit the maximum extent of VDL loading by the rebroadcaster; (2) Govern transmitter duty cycles and overall power consumption; (3) Provide the surveillance reception process with advance notice of when (slot numbers) rebroadcast messages are most likely; (4) Create a “logical barrier” for the surveillance software to use to protect from accepting false rebroadcasts received during “unrecognized” slots (cybersecurity feature); (5) Support the option to reserve FATDMA protected slots in the local area of the surveillance station.

To be determined is the rule base defining how the rebroadcaster's configured slots are used during operation. For example, should the use of a slot “time-out” be the same as Class A reservations; or once the use of a slot begins, should that slot's reservation be continuously refreshed until that slots bandwidth is no longer needed.

The radio-link would perform the best when the slots are protected with fixed slot reservations at both ends. FATDMA requires the surveillance site to have a transmitter that transmits base station messages. A fixed reservation structure ensures the most polite VDL and requires the minimum of operational management.



A.2.4 Retransmission scheduling

Mobile AIS units reserve time slots using SOTDMA. In order to minimize simultaneous transmission interference as the units move relative to each other, mobile AIS units are required to only hold slot reservations for a few minutes. When the slot reservation “times-out” the AIS unit changes its reservation to another slot based on its knowledge of other AIS units’ slot usage – this is each units “frame map” (slot reservations list). Fixed AIS units, such as, AIS base stations use fixed slot allocations that do not change. This is called a FATDMA reservation and can only be made by stations with certain characteristics. One reason for this convention is that the shore stations do not always use their slot; but need to have it ready when it is needed. Simulations and years of AIS experience indicate that this remains the more polite option for VDL use by shore stations.

Taken from: IEC 62320-3: §4.1.2.3 – Message rescheduling:

“This mode is only applicable for scheduled position reports.”

“Received messages shall be analyzed and the repeater station shall reschedule transmissions using an ITDMA schedule.”

“The repeater station may reschedule repeated messages using a reporting interval different from the original interval, depending on configuration.”

Potential Rebroadcaster requirement for message scheduling.

The available slots shall be as configured. Slot use will be governed by rules still to be determined. Slot reservations shall be maintained using SOTDMA. First time slot reservations shall be done using ITDMA.

Discussion

A simplex repeater is required to transmit received messages within a configured time interval after reception, not to exceed 9 seconds. More details of the “General repeating rules” for a simplex repeater can be found in IEC 62320-3: §4.3. There are a number of practical reasons why this is necessary. A very important reason has to do with the UTC “time” of a retransmitted position report message. An AIS position report contains only the UTC seconds portion from the navigation solution. This data short-cut was taken to minimize the number of bits needed for the position time stamp. Because AIS is designed to operate in real-time and all stations have identical internal clocks (GNSS synchronization) the position time stamp in seconds is sufficient for unambiguous interpretation of the navigation solution time. Navigation systems often use this time tag to dead reckon vessels’ positions.

Recognizing that a surveillance system’s analysis does not necessarily operate in real-time, the NAIS collection of AIS messages records the reception time of each message with a full UTC time stamp using Unix time (also known as POSIX time or epoch time) – seconds past midnight of January 1, 1970 minus the number of leap seconds added since then.

The “Extended Range” message described in Appendix C also records and reports the rebroadcast messages reception time along with each message that is rebroadcast. Inclusion of a complete “time-stamp” as message metadata relaxes the need for rebroadcast repeater messages to be retransmitted in less than 9 seconds. Rather the retransmission schedule can be determined by the time requirements of the surveillance authority. It is quite reasonable to assume messages could be delayed for minutes before being retransmitted. The important point is that the exact time of the message’s position solution is preserved inside the retransmitted message (See Appendix C for details.).



A.2.5 Selection of messages for retransmission

The IEC simplex repeater standard (IEC 62320-3: §4.3 Repeating rules) contains a seven page section describing message retransmission filtering options. The filters are useful for reducing the number of retransmissions; but the filtering process need careful adjustment to support a sufficient retransmission frequency for each vessel in order to maintain real-time tracking suitable for navigation decisions. The purpose of AIS technology supports the use of repeaters; because the repeaters provide more navigation information.

The selection of messages for retransmission by the rebroadcast repeater will not be driven by navigation requirements. The purpose of AIS technology does not support the use of repeaters for communications; but AIS does support the objective of maritime surveillance – a careful balancing act that needs to be respected. For the same population of vessels, the rebroadcast repeater is expected to retransmit significantly fewer messages. The primarily reason is politeness. The rebroadcast repeater will be transmitting communication messages that contain surveillance information not intended for navigation use.

The careful balance between navigation and surveillance can create an information bandwidth issue for a rebroadcast repeater. While remote traffic areas, such as in Alaskan waters, may have unlimited bandwidth available (little marine traffic); other areas, such as the monitoring of offshore traffic in the Gulf of Mexico could have only limited bandwidth available of AIS surveillance messages. Future development of rebroadcast repeater message filtering options is anticipated to require careful attention to the update rate needed by surveillance processes being fed and an effort to politely obtain enough VDL information bandwidth to support the level of service needed.

The delivered capability has an exposed “controller” that can be easily modified to field and test different message filtering methods. Figure 5 shows an “External PC 1 Rebroadcast” computer in the lower left corner. This “Rebroadcast” computer is the delivered capability’s equivalent of the controller shown in Figure A-1. The “Rebroadcast” control software is written in the Python computer language and the operating system is Xubuntu. The rebroadcast software is written with a few basic filter options, such as, distance, direction, and message type. These test options are not based on surveillance requirements. They were selected for equipment testing and concept demonstration. They can be changed to evaluate real surveillance requirements.

The drafting of the rebroadcast repeater message-filtering rules is expected to require substantial interaction with the consumers of surveillance information – both within and outside of the USCG. This effort does not attempt to define the needed functional requirements; but only a few basic rules that are used to assess the equipment’s message transmission and reception methods.

A.3 Comparison of Standard AIS Repeater and Rebroadcaster VDL Loading

This section looks at the impact that a repeater and rebroadcaster each could have on the AIS VHF Data Link (VDL). In particular, when the primary intent of the retransmitted messages is to improve the performance of the existing surveillance infrastructure. First, the observed impact of a repeater is presented. Afterward and using the same repeater observations, a similar graphic is synthesized to visualize the estimated impact of a rebroadcaster. The intent is to provide a visualization of how the rebroadcaster could use the VDL more efficiently. The rebroadcaster reduces overall VDL slot usage while extending reception range. Reduced VDL use generally improves the overall reception performance of an existing shore based infrastructure.



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The method used to visualize both reception range extension and VDL loading is the plot of AIS message signal strength versus the distance between the AIS unit and shore surveillance receiver (See Figure A-2.). Over a 24-hour observation period, multiple messages with the same pairing of signal strength and distance occur. To track these repeat pairings, different colors are used. Figure A-2 consists of the observed data organized into cells 1-dBm high and 1-NM (nautical mile) wide. The cell color indicates the number of different AIS messages received over a 24-hour day that have the same cell dBm-NM coordinates. The color relationship to messages with the same dBm-NM coordinate (or density) is shown by the color bar on the right side of Figure A-2.

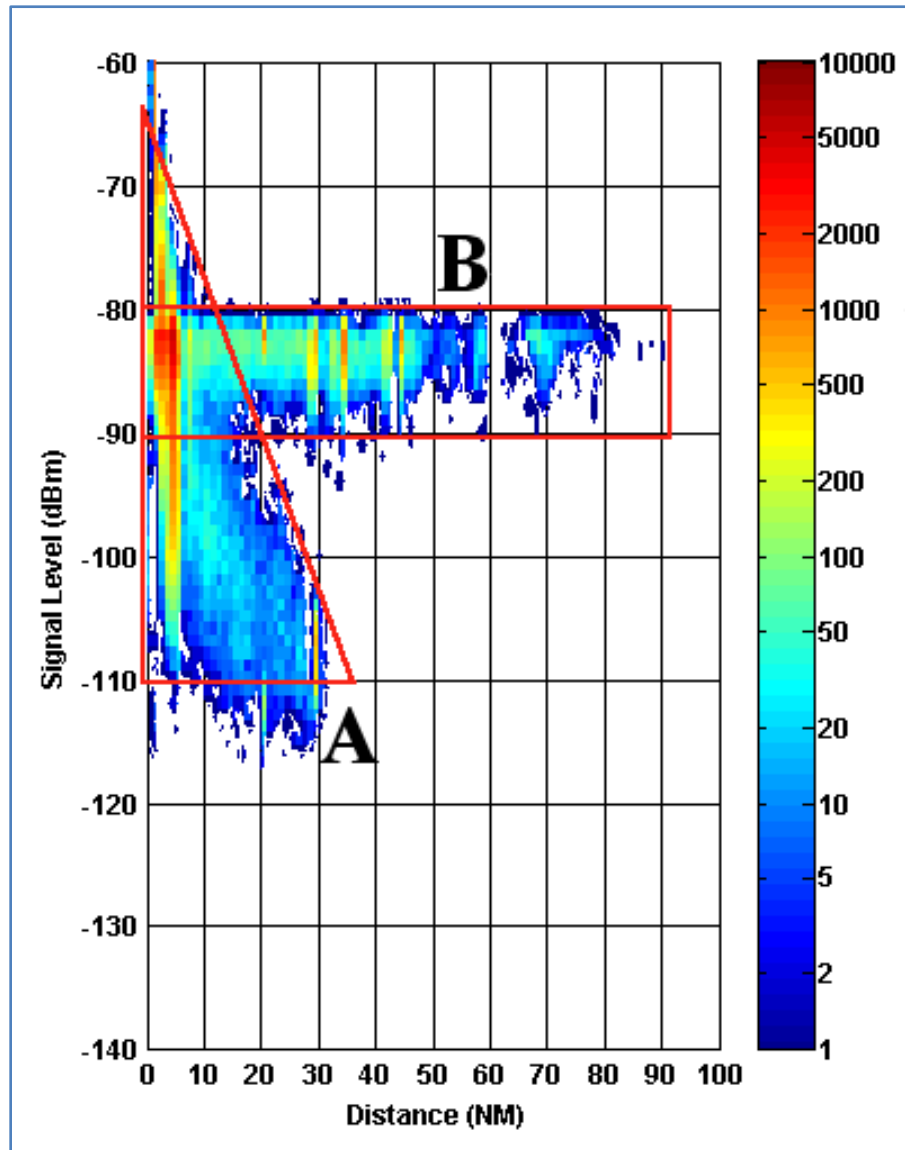


Figure A-2. Sample AIS message count density by signal level and distance for a 24-hour sample period (See text.)

Because AIS units transmit with a known fixed power level and similar vertical antennas, their signals can be used to characterize the reception performance of a surveillance site. By measuring the strength of these messages and organizing the measured message signal strengths using a geographic relationship (such as



range-distance) relative to the reception site, the coverage area of an AIS surveillance site can be accurately estimated without conducting a separate (and at times expensive) formal reception survey. Also, as changes are made to the antennas and equipment at the surveillance site, reception performance can be easily reevaluated without a formal reception survey.

In a more general study of AIS area coverage other graphical plots could be used to evaluate distortions in coverage area caused by topographic signal obstructions - islands, hills, and mountains. An example of such a plot was introduced earlier, see Figure 2. However, in this study the radio-link of interest is between two stationary locations, and Figure A-2 is the better graphical form to discuss AIS message reception augmented using point-to-point message retransmission. In particular, because the retransmitted messages have a narrow range of signal strengths that help in visualizing the path by which they are received.

Figure A-2 is the “signal level vs. distance plot” resulting from AIS signal measurements made at a fixed location along the Columbia River. Also operating in the area was an AIS repeater located on a mountain. The signal strength measurements of AIS signals received directly from AIS units generally fall inside triangle A. The cell colors represent message count totals organized into cells that are 1-dBm in strength by 1-nautical mile of distance. Note that some cell colors indicate over 1000 messages received. This is typical for areas with active port and channel traffic. In Figure A-2:

- The “A” triangle indicates totals from messages received directly from the AIS units,
- The “B” rectangle indicates totals from messages received via the repeater,
- The intersection of triangle “A” and rectangle “B” is the sum of direct and repeater,
- The vertical axis of Figure A-2 shows the signal strength of the received message,
- The horizontal axis shows the distance between the AIS unit and reception site at the time the message signal strength was measured, and
- The color indicates the total number of messages received for each cell – a combination of signal strength and range-distance.

In an area with many moving AIS units, a good coverage estimate can be made over a 24 hour period. In areas with few AIS units, it could take weeks to record enough measurements to estimate coverage. This coverage assessment method can also be used over time to detect reception coverage changes.

A.3.1 Repeater VDL loading impact

Methods presented in this report address issues visible in Figure A-2. The bottom of the A-triangle marks the approximate low end of the reception sensitivity of the infrastructure’s receiver (about -110 dBm). Note that this is not a hard limit because of radio noise. The “fuzzy edge” under the A-triangle is an indication that the impact of radio noise at the receiver detector is variable. This task and report devote considerable effort on delivering a capability that could reduce the impact of noise, reduce “fuzz” and lower further the bottom of the A-triangle; improving the effective sensitivity of the receiver.

Also, note that very close transmissions, left lower corner of the A-triangle, can be weak. This is caused by either signal path blockage or Rayleigh Fading (signal self-interference). These are not equipment issues; rather, they are due to the operating environment and antenna installation decisions – location and orientation. In operation, these types of issues should be temporary because the transmitting unit is mobile and moving.



The A-triangle captures the “classic” profile of marine surface-to-surface radio-link performance. For this installation the AIS reception range appears to be about 30 NM.

In this example, the messages retransmitted by the repeater significantly extended the infrastructure’s reception performance. Notice the faint light blue vertical line crossing the bottom of the A-triangle at the 21 NM point. Then follow the 21 NM line up to the B-rectangle and note the yellow and orange band at 21 NM. The B-rectangle indicates significantly more information in the form of more messages arriving via the repeater. Similarly, at the 29 NM point along the bottom of the A-triangle is another yellow line shows a good amount of messages; but the line at 29 NM inside the B-rectangle shows even more messages. Beyond 30 NM the B-rectangle shows additional bands providing more messages to the infrastructure whereas the A-triangle reception is non-existent.

In this example, the repeater signals average about -83 dBm. This is a generous signal with respect to the A-triangle sensitivity floor of -110 dBm. The repeater signal varies between -79 dBm. and -94 dBm. This is sufficient to expect most of the repeater messages to be received. Although both the infrastructure receiver and repeater have a fixed geographic relationship (neither is moving), this variation in the strength may seem large; but in fact, this value is typical. This level of signal variation is caused by the changing atmospheric propagation conditions between the two sites, plus other odd causes, such as, signal reflections off of passing aircraft. In planning a radio-link, this variation (here about 15 dB) is often referred to as the link-margin; and when planning radio-links, deciding this value helps establish other controllable link-budget adjustments such as the necessary: antenna gain, transmitter power, and receiver sensitivity. For point-to-point communications, it is common to conduct a preliminary radio signal based survey of prospective sites to measure the actual path loss and link-budget to the prospective sites before undertaking a cost estimate for a site’s permanent development.

If the deployment paradigm is to “use locations of opportunity” (existing locations with power, enclosures and security), going directly to temporary deployment, rather than a preliminary radio survey, is a cost and time effective approach. The author has used this approach to advantage in reducing deployment costs and deployment delays; but these temporary deployments need to include a serious effort to analyze the resulting site performance. This approach is particularly effective when the temporary equipment that is installed has a well understood performance level (a referenceable level of performance), and the alternative methods and costs to boost that level of performance, if needed, are also already understood.

In Appendix B that follows, the radio-link elements are presented along with more detail about how the performance of the radio-link can be adjusted.

A.3.2 Rebroadcaster VDL loading impact

Earlier in this Appendix, the point was made that AIS message retransmissions in support of surveillance should be governed by requirements that are different than the navigation requirements that govern the design and operation of the current IEC repeater. This section presents additional notions that should be considered as further development of AIS surveillance requirements go forward.

Figure A-3 is a graphic modification of Figure A-2. It is intended to provide a visual presentation of how the analysis of the AIS message reception shown in Figure A-2 might change if the repeater were replaced by a surveillance based rebroadcaster.



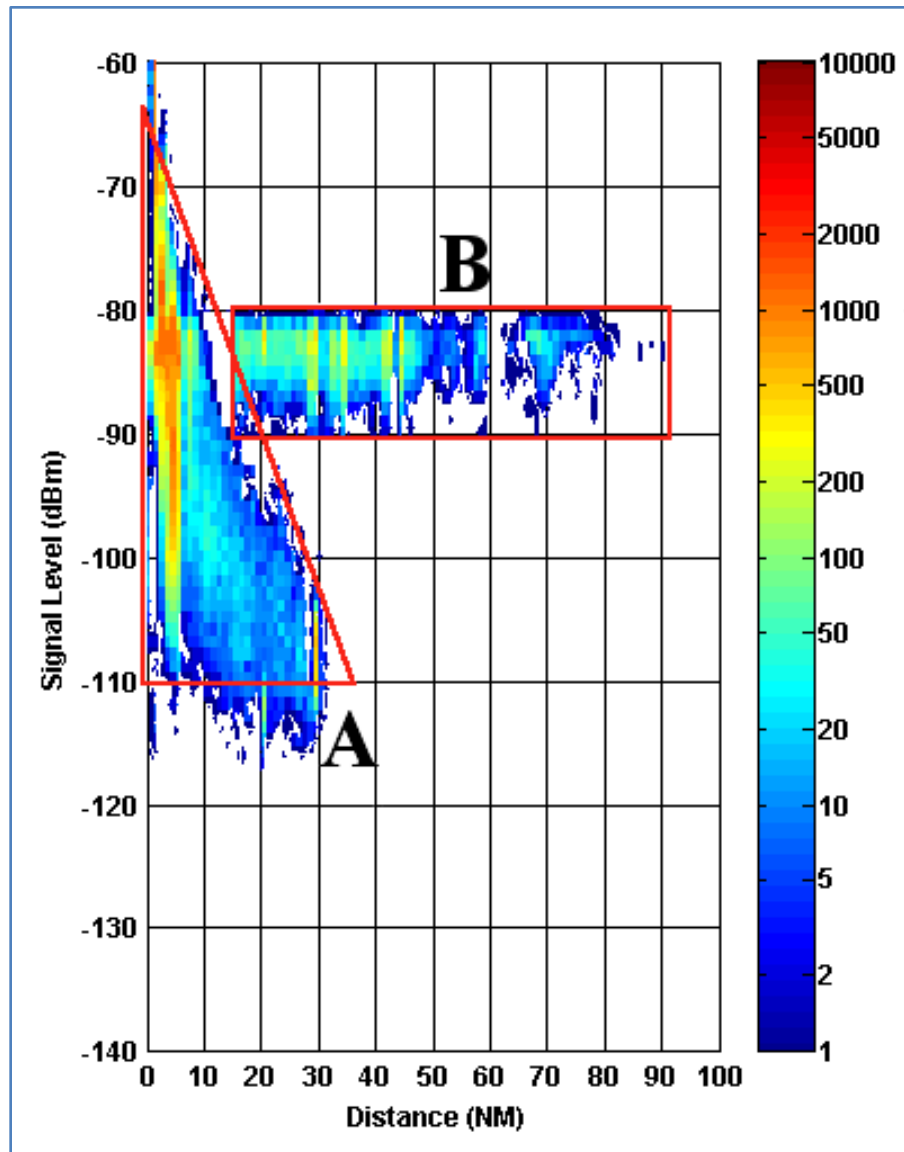


Figure A-3. Example of change to Figure A-2 count density if the repeater is replaced by a rebroadcaster (See text).

The most obvious change is the dimensions of the B-rectangle. The primary purpose of the rebroadcaster is to extend the reception range of the surveillance infrastructure; and to do this with a minimum loading impact on the VDL. If the surveillance site receiver sufficiently monitors an area, the rebroadcaster need not rebroadcast messages originating from that area. Figure A-2 showed a significant overlap of the A-triangle and B-rectangle. Figure A-3 shows that the rebroadcaster is not retransmitting any messages within 15 NM of the surveillance site. Note there remain retransmission of duplicate messages in the B-rectangle, between the 15 NM point and the right end of the A-triangle. In fact, the coverage of this range is more reliable via the rebroadcaster than the surveillance receiver – due to the mountain top location of the rebroadcaster.

In addition to the dimensions of the B-rectangle changing, the number of retransmissions inside the box would be reduced for various reasons – depending on the rebroadcaster’s rules governing message retransmissions. In Figure A-3 the cell-colors are changed slightly to show fewer total messages. There may

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be some areas greater than 15 NM that are sufficiently covered by the infrastructure receiver. It may not be necessary to retransmit messages from these areas, as well. This results in color changes showing fewer messages on the left side of the B-rectangle to show fewer retransmissions. The rebroadcaster may be limited to the use of a fixed number of slots in each frame. This would place a rigid limit on the total number of messages inside the B-rectangle; and place a premium on the rule base deciding which messages are retransmitted.

The rebroadcaster's rule base for selectively retransmitting messages is yet to be developed; and the development needs to be based upon surveillance requirements. The capability delivered as part of this task incorporates a few experimental rules to demonstrate the capability; but deciding a standard set of rules needs to be a future effort undertaken with the participation of the surveillance community.



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APPENDIX B. RADIO LINK BUDGET

B.1 Background

The radio link budget captures the primary factors that affect the energy or power of a radio communication signal and the ability to receive that signal. The relationships of the primary factors is expressed in a single high level equation; however, behind each factor is its own set of equations. The equation can be reorganized to help understand the work that needs to be done to improve a radio link and the cost or effort that might be needed to achieve a favorable outcome. Depending the particular factor, communications can be improved by a physical change, such as, changes to the antenna; or through technological change, such as, improved signal processing at the receiver.

B.2 Radio Link Budget Equation

The strength of a radio signal from a transmitter at the receiver is estimated using the following “Radio Link Budget” equation:

$$P_{RX} = P_{TX} - L_{TX-LINE} + G_{TX-ANT} - L_{PATH} - L_{SIG} + G_{RX-ANT} - L_{RX-LINE}$$

Where:

P_{RX}: The power level (energy rate) measured at the input to the receiver during reception of a desired transmission. It is most commonly expressed in units of “dBm” – the abbreviation for “10 times the log₁₀ of the ratio of the power measurement to a one milliwatt (0.001 Watt) reference level.

$$\text{dBm} = 10 \log_{10} ((\text{measured power}) / (\text{one milliwatt})).$$

Decibels are the units of choice when making radio link calculations. Decibels are logarithmic units; and radio equipment specifications are frequently published using decibel units, such as, dBm or dB. Expressing the elements of the Radio Link Budget in logarithmic units allows their power impacts in “dB” to be added or subtracted to calculate the power at the receiver.

[Technical Note: A Watt is equivalent to one joule per second. AIS signal transmissions are less than one second in duration. To be more exact, a single slot “12.5 Watts” AIS signal is really a 12.5 joule signal of 26.6 millisecond duration. The actual power in this 12.5 joule signal is $12.5 \times 0.0266 = 0.333$ Watt. In general, the link budget calculation views the radio channel as if the transmitter signal is continuous and the discussion of the link refers to signal levels in Watts. This report uses this traditional convention in discussing the radio link.]

P_{TX} The power level measured at the transmitter output in dBm. For example, the high power output of a “Class A” AIS unit is at a level of 12.5 Watts, or $10 \log_{10} (12.5 / .001) = + 40.97$ dBm.

L_{TX-LINE} The reduction of a signal’s power in dB due to the cable transmission line between the transmitter output and transmitter antenna input. This is transmitter signal power lost to resistance and impedance matching issues.

G_{TX-ANT} This is the effective power gain created by the transmitter antenna design measured in the direction of the receiver antenna location in dBi. This may not be the published “gain” of an antenna depending on the nature of the area where the antenna is installed and the orientation of the antenna to the reception location.

L_{PATH} Loss of transmitter signal power level as the signal propagates from the transmitter antenna to the receiver antenna. Path loss is very sensitive to antenna heights and topography. Once determined, this loss can slowly vary with time around a fairly constant value. Propagation modeling software can provide reasonable estimates; but there is no substitute for doing point-to-point site surveys.



- L_{SIG}** Loss of transmitter signal power level due to “other” and usually short term conditions, such as, signal blockage by an object or weather (heavy precipitation). There are conditions that can cause this value to be negative (a signal gain), for example, tropospheric ducting or signal reflections off of aircraft.
- G_{RX-ANT}** This is the effective signal power gain produced by the design of the receiver antenna as measured in the direction of the transmitter antenna location in dBi. As is the case with **G_{TX-ANT}**, this may not be the published “gain” of an antenna depending on the nature of the area where the antenna is installed and the orientation of the antenna to the reception location.
- L_{RX-LINE}** The reduction of power between the receiver antenna and receiver input in dB. Like the transmitter line loss, this is transmitter signal power lost to resistance and impedance matching issues, but at the reception site. At facilities where the receiver antenna is dedicated to reception, a pre-amplifier is installed at the output of the antenna – effectively reducing the antenna to receiver connection to a few feet of cable. For these installations the loss is considered negligible, and the cable between the pre-amplifier and the pre-amplifier are essentially part of the receiver.

Not included in the link budget equation is the power of the radio noise added to the signal at the input of the receiver (**P_{NOISE}**). **P_{NOISE}** is not part of the “desired signal” and it did not travel the same propagation path as the signal; but it is an important factor affecting the reception performance of the receiver. It is mentioned here in order to expose the fact that noise does impact total power and that the power balance between signal and noise impacts the performance of the receiver’s detection / demodulation signal processing. A fact that is important to understanding how a receiver’s “effective” sensitivity can vary during operation depending on the nature and number of the bits inside the signal and the dynamic radio-noise environment. The published sensitivity of AIS receivers are usually based on a testing process that uses a 20% packet error rate (PER) criteria to establish the receiver’s sensitivity. This test is traditionally done using a cabled connection environment that excludes, by design, radio frequency noise during testing.

B.3 Using the Link Budget Equation

As the radio link requirements change, the link budget equation can be used to identify factor nuances that show promise for developing new methods and making technologic advances. The following discussion considers changes possible when the application of AIS shifts from ship to shore surveillance to point-to-point communications. Point-to-point communications is the case where the linking of shore surveillance sites using the AIS VHF data link is under consideration.

The link budget equation can be reorganized to separate the propagation factors, **L_{PATH}** and **L_{SIG}**, to the left side of the equation. The reason for moving **L_{PATH}** is to set aside discussion of antenna height from consideration as a method for improving radio link performance. The communications benefit of a high antenna is understood and height is used to advantage when available; however, for AIS equipment deployment in Alaska, antenna heights for both ships and shore stations will be considered about the same. The **L_{SIG}** value should be more stable for point-to-point communications; and will be discussed in the context of improving factors on the right side of the equation. The factors on the right side of the equation will be further investigated to see how they can be improved as the operating requirement changes from wide area surveillance to point-to-point communications. [Note: The value of **P_{RX}** is measured in negative dBm. After being moved to the right side of the equation, a further reduction of **P_{RX}** is a positive improvement.]

$$L_{PATH} + L_{SIG} = P_{TX} - L_{TX-LINE} + G_{TX-ANT} + G_{RX-ANT} - L_{RX-LINE} - P_{RX}$$



B.3.1 Typical link budget values

Table B-1 lists typical values of link budget factors for three different AIS uses – where the equipment is defined by IEC standards and installed following IMO guidelines. The two point-to-point examples do not conform to an IMO standard and reflect the changes due to the requirement shift away from area reception.

The following is a bullet discussion of the Table B-1 contents:

- Although the link-loss tolerance is similar for the three AIS examples; this does not mean their operational performance is similar.
 - The base station and repeater antennas are normally installed higher than a ship's antenna.
 - The same link-loss tolerance buys more area coverage (range) as the antenna goes higher.
- AIS antennas are normally omni-directional to cover the surrounding area.
 - The point-to-point examples can use a directional antenna.
 - A repeater could use a directional antenna to broadcast repeated messages in a selected direction; but it would normally use an omni-directional antenna for reception.
- Increasing the P_{TX} power level needs to be done with caution as to not disrupt AIS operation.
 - Because AIS messages are short, transmissions at higher power (case 2) may not require a significant change in electrical power, if the transmissions are infrequent.
 - A rebroadcaster broadcasts based on surveillance requirements that lessen the need for frequent updates on all of the vessel messages being received.
- The P_{RX} improvements of cases 1 and 2 may not be realized if L_{SIG} and P_{NOISE} are ignored.
 - P_{RX} is measured without L_{SIG} and P_{NOISE} being present.
 - To fully benefit from P_{RX} improvements, measures need to be taken to lessen L_{SIG} and P_{NOISE} . (See “Bit Error Probability” below.)

Table B-1. Link budget values for AIS.

Link Budget Factor	Ship to ship Class A	Ship to IEC Base Station	IEC Repeater	Case 1 Point-to-Point	Case 2 Point-to-Point
P_{TX}	+41 dBm	+41 dBm	+41 dBm	+44 dBm	+51 dBm
$L_{TX-LINE}$	- 3 dB	- 3 dB	- 3 dB	- 3 dB	- 3 dB
G_{TX-ANT}	+ 4.5 dBi	+ 4.5 dBi	+ 4.5 dBi	+ 11.6 dBi	+ 14.8 dBi
G_{RX-ANT}	+ 4.5 dBi	+ 9 dBi	+ 9 dBi	+ 11.6 dBi	+ 14.8 dBi
$L_{RX-LINE}$	- 3 dB	- 3 dB	- 3 dB	0	0
P_{RX}	- (- 107 dBm)	- (- 107 dBm)	- (- 107 dBm)	- (- 119 dBm)	- (- 125 dBm)
Link-loss Tolerance	151 dB	155.5 dB	155.5 dB	183.2 dB	202.6 dB

B.4 Bit Error Rate

The following begins to describe the developmental work of this effort.

The primary purpose of AIS is the distribution of information about a ship and its movements to those navigating vessels in the same area. The key navigation information is contained in a digital radio packet of about 200-bits of data. The nominal interval for transmitting this message is every 10 seconds; but this interval may be increased or decreased, depending on the vessel speed or rate of turn.

The sensitivity of an AIS receiver, P_{RX} , is determined in a test environment by the signal level at which the receiver fails to receive more than 20% of the 200-bit AIS message packets. The AIS message packet contains data (16-bits) used to detect an error – cyclic redundancy check (CRC). If the CRC fails for the AIS message in the packet, the entire message is not considered valid. In effect, the P_{RX} is the signal level where the bit error rate (BER) of the receiver is about 10^{-3} – one incorrect bit in every 1000.

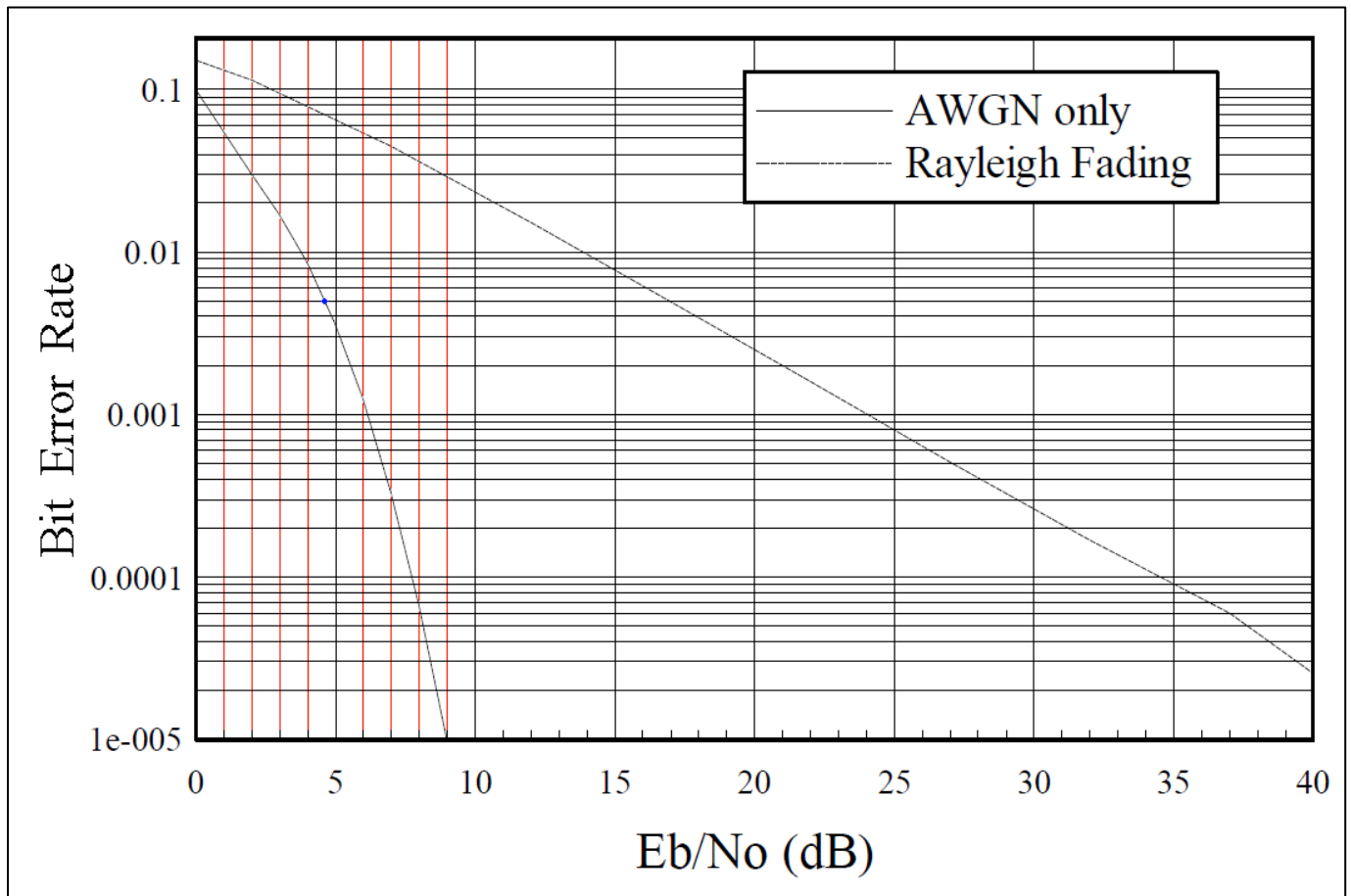


Figure B-1. BER versus E_b/N_0 for a GMSK demodulator in Additive White Gaussian Noise (AWGN) and Rayleigh Fading.

Figure B-1 shows a modeled bit error rate (BER) for a GMSK demodulator as a function of the ratio of a signal's power to the noise level. Also shown, is the impact of Rayleigh Fading on the BER. N_0 , the noise power, is the portion of P_{NOISE} that is present at the demodulator input along with the signal. Rayleigh Fading is a significant contributor to the L_{SIG} – the signal loss factor. In general, noise energy and signal degradation phenomena, like Rayleigh Fading, tend to vary with time, radio frequency, antenna polarization, and the signal path. The conclusion is that BER can be reduced if the P_{NOISE} and L_{SIG} factors' impact on the demodulation process can be reduced or avoided by taking advantage of their variations in the four dimensions of time, frequency, polarization, and path.

If this approach were successful, it would seem to be of greatest benefit at the worst of sites. A well-engineered site may not realize a significant performance improvement; but a more marginal site could realize a significant improvement – perhaps a good outcome for remote sites with low antennas.

B.5 The AIS Hardware Complications and Solutions

One ingredient to evaluating methods in each of the four dimensions is the transmission of the identical data packet in each dimension. Unfortunately, design features of all AIS equipment creates an issue with using existing equipment to conduct laboratory and field tests. They are:

- Bit-stuffing,
- Single transmitter, and
- Discarding corrupted messages.

The purpose of bit-stuffing is to add bits to the AIS data to avoid having the data packet's "start" or "end" flag appear inside the AIS message data. This is a mechanical bit handling process in both the transmitter and receiver. The primary complication is that the signal testing levels in each dimension would be at data corruption thresholds. The data bits corrupted could be the stuffing-bits added at the transmitter. The resulting mechanical process could then pass stuffing-bits as data, and interpret data bits as stuffing-bits. Removing the data bits from the packet without notice. This issue has a "fix." Do not transmit messages that require stuffing-bits to be added. This is discussed in detail in Appendix D.

In order to simultaneously transmit the same message on each of the two AIS channels, two transmitters are needed. All standard AIS equipment contains one transmitter. Rather than build a new two transmitter device, the "fix" for this issue is to use two time synchronized Shine Micro AtoN units.

In order to investigate how the message data is corrupted at low signal levels, it is necessary to record and analyze the corrupted message's bits. AIS equipment is designed to not provide these messages. In order to obtain the corrupted messages, the operation of two government receivers was altered. This required the development of a firmware upgrade to the government owned receivers, the creation of a proprietary NMEA sentence to record the data, and detailed testing of the final implementation.



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APPENDIX C. AIS MESSAGE MEASUREMENTS (METADATA)

C.1 Background

The rebroadcast process needs to capture information about, and bind that information to, each message received. This information about the message (metadata) provides permanent context for interpretation of the message and subsequent action or analysis using the data. This appendix contains a discussion of each metadata item rebroadcast along with the original message.

An important characteristic of the rebroadcast site's operation is that the number of transmitted packets is limited. The initial intent is to limit the number of rebroadcasts to about ten 2-slot packets per minute. As a result, most of the messages received will not be rebroadcast.

C.2 Metadata Items

Time:

Because AIS is designed for use in real-time, that is immediately; each message contains little clock time or calendar information. The "time" metadata form used for this task, "frame" and "slot," provide time information on a daily cycle. They also provide good information about the general health and operation of the equipment. The surveillance site is expected to add another time-tag to the data when the rebroadcast message is received.

The "Reception Frame" is an 11-bit binary integer from the first minute of the Greenwich Mean Time (GMT) day 0 (00000000000₂) to the last minute of the day 1439 (10110011111₂). This value should reset to 0 at the beginning of the GMT day. This value is 2047 if unavailable.

The "Reception Slot" is a 12-bit binary integer of the messages starting AIS slot, 0 to 2249 (with a maximum binary value of 100011001001₂). This value resets to 0 at the beginning of the next frame. This value is 4095 if unavailable.

This time tag is important, because the rebroadcast queuing rules may result in some message's rebroadcast being delayed for several minutes. If time is clearly known, a reported position and calculated dead reckoned positions are fairly accurate; but a misunderstanding of a time-tag could put a vessel's position elsewhere by miles. This would be the case if the rebroadcast messages "time" were used to dead reckon the position.

Time Source:

This is a single binary bit indicating the time source being used. A binary 0 indicates the use of the internal real time clock and a binary 1 indicates the use of GPS. The current design of the system requires that the two transmitter (SF-162AtoN-T3) units have a GPS timing source. If there is an issue with a units GPS or GPS antenna, the unit will not transmit. Note that the units use independent GPS antennas.



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Signal Strength:

The signal strength of the message is a 7-bit binary integer that quantifies the signal in 1 dBm increments from a binary 0 (representing -20 dBm.) to a binary 127 (representing -147 dBm).

Note that the rebroadcast site can use up to four antennas to receive messages, each antenna with its own unique reception pattern. Over time, the relationship of the relative signal strengths of each receiver-antenna to each other can be determined and the resulting geographic database used to estimate if the message's transmitter is located in the approximate area reported in their AIS message. This process need not be done at the rebroadcast site; but could be operating at a central facility. The objective of the process would be to flag AIS message sources that provide suspect message information.

Phase Difference (provision for future addition):

The reception phase difference of a signal between two receiver-antenna combinations can be used in a way that is similar to the use of signal strength. The phase difference measurement is a 9-bit binary integer that quantifies the difference from a binary 0 (representing 0 degrees) to a binary 359 (representing 359 degrees). Note that the phase measurements are not direction finder-like. The receiver antennas do not need special attention to configuration, alignment, or antenna design. These measurements would be used over time to develop a geographic database to detect and flag AIS message sources that provide suspect message information. This feature is currently unavailable and the value is set to 511 (11111111₂).

Noise Floors (Channel A (AIS1) and Channel B (AIS2)):

This is a 5-bit binary integer that quantifies the noise floor measurement in 1 dBm increments from a binary 0 (representing -100 dBm.) to a binary 31 (representing -131 dBm). The SM1680 provides a combined receivers noise floor for each AIS channel. This is used to detect and monitor reception issues at the rebroadcast site.

Reception Channel:

The AIS channel upon which the message is received is indicated with a binary 0, if the message is received on AIS1 (161.975 MHz.); indicated with a binary 1, if the message is received on AIS2 (162.025 MHz.). Note that, unlike the repeater standards, the message can be rebroadcast on either AIS1 or AIS2 without consideration of the channel upon which it was received.

Skipped Message Rebroadcasts:

Each rebroadcast message should be the most current version of that message-type received from an MMSI. This could be different depending on the Rebroadcast software message filter settings. In any case there will be a number of messages received from an MMSI between the rebroadcast of a message from that MMSI and the next rebroadcast. In other words, a number of messages will be received from an MMSI and discarded rather than being rebroadcast. It is important to know the number of messages discarded. It is useful to know if the MMSI is operating within the AIS rule set. This is an 8-bit binary integer (a range from 0 to 255) that is reset to zero each time a message from that MMSI is rebroadcast.



Rebroadcast Message Cyclic Redundancy Check (CRC):

Commercial AIS equipment does not output the CRC of a successfully received AIS message. The desire for the rebroadcast capability was to rebroadcast the message exactly as received. To accomplish this, the Rebroadcast software recalculates the correct for the CRC after the message is received from the SM1680. This makes it possible to again perform the CRC test on the message contents, if desired, further down the surveillance data-flow chain. This is expected to be important as methods are developed and tested to recover bits lost to noise as when the rebroadcast signal becomes weak relative to the surveillance site noise floor.

Unassigned Bits:

As delivered, there are currently 5 bits in the metadata porting of the rebroadcast message structure that are unassigned. They are set to a binary 0. Currently, a rebroadcast message is not transmitted if the message contains a “stuffing-bit.” After all the precautions were taken, there remained the possibility that the message CRC would require a stuffing-bit. The work around taken is to not transmit those messages. An alternative would be to change one or more of these unassigned bits until the CRC did not require a stuffing bit. This would be a future work item to consider.



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APPENDIX D. EXPERIMENTAL “EXTENDED RANGE” MESSAGE

D.1 AIS Radio Packet Structure

This appendix contains the information about how the Type 26 AIS message is used to rebroadcast an AIS message along with attached metadata about the message, and the use of a “zero- fill” pattern that keeps the automatic HDLC process from adding stuffing bits to the message.

The structure of the digital bits within an AIS radio signal conform to elements of the high-level data link control (HDLC) synchronous framing structure defined in ISO/IEC 13239:2002 (or the earlier ISO 3309). The key elements of HDLC structure used in AIS equipment (that can create issues in a “noisy radio environment”) are (1) the use of start and end frame flags and (2) the subsequent need for bit stuffing.

Each AIS radio packet begins and ends with the bit string “01111110,” which is called a “flag.” Because this “flag” consists of six consecutive 1-bits, the other data within the radio packet is coded to ensure that it never contains more than five 1-bits in a row. This is done by “bit stuffing.” That is, after every occurrence of five consecutive 1-bits in the transmitted data, a 0-bit is added to the transmitted data – this results in these structural bits being added to the radio packet contents at “random” locations determined by how the ones and zeros appear in the data! This works well in systems where the transmit signal is well above the noise level; but they cause problems in noisy communications connections.

After AIS packet reception and demodulation the receiver must remove the stuffing “0-bits” added at the transmitter. The receiver is designed to detect five 1-bits in a row. After the fifth 1-bit, the following 0-bit is stripped out of the received data. If instead the sixth bit is 1, this is either an “End flag” (if the seventh bit is 0), or an error (if the seventh bit is 1). In the latter case, the packet reception process is aborted, to be restarted after the next “01111110” flag received.

As the distance between the transmitter and receiver increases, and the radio signal becomes weaker, the receiver demodulation begins to make mistakes interpreting if the next received bit is a “1” or a “0.” As mistakes are made, the stuffing bit removal process sees a different series of ones and zeros than existed at the transmitter stuffing bit insertion process. This results in an “information change” within the AIS message. Under normal circumstances, the following processes in the receiver, such as, the CRC test catch the fact that the information has changed and the entire corrupted message is discarded and the process aborted.

D.2 AIS Messages without Stuffing Bits

Is it possible for an AIS message to not have any stuffing bits? The answer is yes! If the AIS message data is such that it does not contain five consecutive 1-bits, the HDLC stuffing process will never add a 0-bit, the AIS radio packet will be a fixed length of bits, and the receiver stuffing-bit removal process will never remove a bit. As the radio signal becomes weaker and the demodulator makes mistakes, an erroneous series of five 1-bits could be “created” and it would be detected by the stuffing-bit removal process and a bit would be removed from the message. As stated above, the rule after the fifth 1-bit is to strip out the following 0-bit from the received data. *(Note that this would shorten the received message by one bit. Since the desired message is known to be a fixed length, the event of a bit removal could be detected.)* If instead



the sixth bit is 1, this is either an “End flag” (if the seventh bit is 0), or an error (if the seventh bit is 1). In the latter case, the packet reception process should be aborted, to be restarted after the next “01111110” flag received.

Can an existing AIS message be used to transmit a fixed length radio packet containing no stuffing bits? The answer is yes if: (1) an AIS “binary” message is used; (2) some care is taken in configuring the AIS unit; and (3) some “data overhead” is added to the coding of the message’s data.

If such a message were to be created and used, does it really change anything of consequence at the receiver? The argument can be made that: *if a data bit is in error, the AIS message will fail the CRC test and the message will be discarded and reception process aborted – basically, the message still “never happened” with or without any stuffing bits. There will be no output from the AIS unit. Besides, why would anyone be interested in receiving a corrupted message?*

It is true that all commercial AIS equipment currently sold does not have the ability to provide a corrupt message. The output format, rules, and content of such an output has simply not been defined. An experimental process to do this will be described below. The experimental process is an upgraded added to the SM1680 and it is designed as a non-commercial method.

With respect to “the interest” question, the objective would be to extract at least some information from messages too weak to pass current reception solution of discarding all the information. With a message that has a fixed and known bit-length, every data bit in the message always occupies the same bit-time within the message. Each bit has a specific positional (in time) identity (you might call it a “bit time-slot”). This can be reinforced if there are known reference bits within the message, bits that can still be identified if the stuffing bit removal process happens to remove one bit ... or more, due to demodulator errors.

If the bit positions are fixed, different corrupted “copies” of the same message can be lined up and compared. If the demodulation processes are independent, the different corrupted copies may be slightly different. At a gross level, the comparison could conclude that portions of the messages are the same and the content probably not corrupted. Other portions of the copies may be different and suggest that the content of those portions of the message have been corrupted “beyond recognition” and should be ignored. At the detailed level, perhaps the corrupted bits contain little information and little information is being lost while the important information is uncorrupted. At the research level, perhaps the construction of the message should be reorganized (the message that follows is “an experimental” message), or perhaps forward error correction methods would be useful and a new experimental message be created for further research. At some time in the future AIS will be upgraded. Are there upgrades to the message coding that should be added to future AIS? The following section describes the experimental AIS radio packet message designed for the current task, and Appendix E describes an experimental NMEA sentence used to deliver messages that fail the CRC test.

D.3 Use of AIS Message 26 for Extended Range Surveillance

The ITU-R Recommendation M.1371-5 defines the details of current AIS technology. These Recommendations define the structure and content of the available types of AIS messages. The existing AIS “Message 26” provides for the transmission of almost any type of binary coded information – up to the data-bit limit.



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Message 26 is titled a “Multiple slot binary message with communications state.” This message is primarily intended for scheduled binary data transmissions by applying either the SOTDMA or ITDMA access scheme. This multiple slot binary message can contain up to 1 004 data-bits (using 5 slots) depending on the coding method used for the contents, and the destination indication of broadcast or addressed.

For the following reasons, the Type 26 message was chosen to carry experimental binary data that includes one AIS position report message and metadata measurement of that message:

1. To maintain radio packet reception compatibility with standard AIS equipment,
2. The Type 26 message can be thought of as an envelope that standard AIS equipment understands, and the experimental content (binary data) put inside the Type 26 message “envelope” will be ignored by standard AIS equipment, thus causing no AIS disruption,
3. The slot reservations made using the Type 26 message are understood by standard AIS equipment, thus the scheduling of experimental transmissions will not disrupt or compromise the use of the VDL by standard AIS equipment, and
4. A two slot Type 26 message provides enough “binary data” capacity to fit: (1) a retransmitted position report message; (2) the message’s metadata; and (3) the extra “zero” bits needed to avoid the automatic addition of stuffing bits.

D.3.1 How Message 26 avoids having “stuffing bits” automatically added

If bit selection were under complete external control, many different messages can be imagined where five “ones” in-a-row never occurs. Unfortunately, that is not the case here. In particular, the content of the AIS position report being retransmitted is under the total control of some unknown AIS unit. The same is practically true about the metadata measurements. That being said, there is a “trick” that can be used.

The bulk of the experimental Type 26 message is the binary data payload. If that payload is artificially constructed with every fifth bit a “0,” the entire payload would never contain five ones in-a-row! If the content of the remainder of the message is configured to not have five ones in-a-row, the automatic stuffing process will never detect five ones in-a-row; and the Type 26 message will be transmitted without any stuffing bits.

A review the first 40 bits (the front of the “envelope”) of the Type 26 message from “Message ID” to the “binary data flag” (See Table D-1) finds that only the bits chosen for the “Source ID” could be a problem; but this is a configurable value and it never changes during operation. So, a Source ID is chosen that does not contain more than four “ones-in-a-row.”

A review of the last 40 bits (the back of the “envelope”) of the Type 26 message from “Spare” to the “CRC” finds several possible issues. The “communication state” is the same type of issue as the “Source ID” above. Operation of the transmitter can be configured, such that, the “communication state” never contains four bits-in-a-row. However, the CRC is a mathematically determined series of 16-bits where the calculation uses every previous bit of the message – it is message content driven. There are two ways to manage this:

1. The delivered version of the transmit control software assembles the prospective message and calculates the CRC. If the resulting 16-bit coding of the CRC value results in five or more ones-in-a-row, the transmission of the message is aborted. It is not transmitted.
2. In the future, the plan would be to change unassigned spare bits in the message to change the results of the CRC calculation. By experimentation and analysis, determine the strongest way to change the



spare bit values to best change the result of the CRC calculation to a bit pattern not containing more than four ones-in-a-row.

D.3.2 The experimental Type 26 message can change

The experimental Type 26 message was designed to begin the investigation of how deeply corrupted AIS messages can be expected to provide some level of recovered information. By “deeply” is meant the signal level at which a significant portion of messages no longer pass the CRC test – perhaps the 20% PER threshold used during standard AIS receiver testing. If testing, in particular field testing, shows the notion of “deep” to be only one or two dB, then maybe the idea of bit repair and partial information recovery is not a fruitful endeavor. However, if deep goes beyond three dB (the “doubling of transmitter power” reference), it may be a worthwhile investigation.

This effort only begins a look towards recovering information from corrupted AIS messages. It provides and demonstrates a way to conduct this research on the AIS VDL without a negative impact on standard AIS operation. Other binary data can bit organizations can be used inside a Type 26 “envelope.” For example, there are a number of forward error correcting methods that may be useful. Selecting the “best” one would depend on the noise characteristics of the AIS channel. This task provides the ability to experiment and compare several types of “channels” – frequency, time, path, and polarization. There is interesting work to be done. In particular, if deep goes beyond three dB.



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Table D-1. Extended range message structure.

Parameter	Number of bits	Description	
Ramp up	8	Transmit “power-up”	
Training Sequence	24	Alternating ones and zeros	
Start Flag	8	Always the pattern “01111110”	
Message ID	6	Identifier for Message 26; always 26 or binary “011010”	
Repeat indicator	2	Used by the repeater to indicate how many times a message has been repeated. Refer to § 4.6.1, Annex 2; 0-3; default = 0 ; 3 = do not repeat any more	
Source ID	30	MMSI number of source station assigned such that binary form does not contain five consecutive “1s.”	
Destination indicator	1	0 = Broadcast (no Destination ID field used) 1 = Addressed (Destination ID uses 30 data bits for MMSI)	
Binary data flag	1	0 = unstructured binary data (no Application Identifier bits used) 1 = binary data coded as defined by using the 16-bit Application identifier	
Destination ID	0 /30	Destination ID (if used)	If Destination indicator = 0 (Broadcast); no data bits are needed for the Destination ID. If Destination indicator = 1; 30 bits are used for the Destination ID and 2 spare bits for byte alignment.
Spare bits	0 /2	Spare (if Destination ID used)	
Binary data	368	See TABLE D-2 for structure and content	
Spare	4	Needed for byte alignment, all bits set to “0”	
Communication state selector flag	1	0 = SOTDMA communication state follows 1 = ITDMA communication state follows	
Communication state	19	SOTDMA communication state (see § 3.3.7.2.1, Annex 2), if communication state selector flag is set to 0, or ITDMA communication state (§ 3.3.7.3.2, Annex 2), if communication state selector flag is set to “1”	
CRC	16	Cyclic Redundancy Check (special handling needed, see text)	
End Flag	8	Always the pattern “01111110.” Note: Signal still at full power.	
Slot timing buffer	16	Transmitter “power-down”	
Total number of message bits	Exactly 432	Occupies 2 slots. The exact number of message packet bits is 464 bits from the beginning of the start flag to the end of the end flag.	
Total number of “radio packet” bits	496-512	This is the length of the radio packet in total bit-times - where one bit-time is 1/9600 second or about 1.041 milliseconds.	



Table D-2. Extended Range Message Binary Data

Parameter	Bits	Binary Data Start Bit	Binary Data End Bit	Fixed “zero” bits	Description	Total bits
RX1 Signal Strength	7	41	48	45	Range from Binary 0 = -20 dBm. to Binary 127 = -147 dBm.	8
RX1-RX2 Phase Difference	9	49	59	50 & 55	Range from Binary 0 = 0 degrees to Binary 359 = 359 degrees 511 = unavailable	11
Reception Channel	1	61	61	---	Reception channel (0 = 161.975, 1= 162.025)	1
Reception Frame	11	62	74	65 & 70	Reception frame (See “Time” in Appendix C.2 Metadata)	13
RX2 Signal Strength	7	76	83	80	(See RX1 Signal Strength)	8
RX1-RX3 Phase Difference	9	84	94	85 & 90	(See RX1-RX2 Phase Difference)	11
Reception Slot	12	96	109	100 & 105	Reception slot (See “Time” in Appendix C.2 Metadata)	14
Skipped Rebroadcasts	8	111	119	115	Missed messages (See “Skipped Message Rebroadcasts” in Appendix C.2 Metadata)	9
RX3 Signal Strength	7	121	128	125	(See RX1 Signal Strength)	8
RX1-RX4 Phase Difference	9	129	139	130 & 135	(See RX1-RX2 Phase Difference)	11
Channel A noise floor	5	141	146	145	Combined receivers noise floor for 161.975 (See “Noise Floors” in Appendix C.2 Metadata)	6
Different MMSIs	8	147	156	150 & 155	Different MMSIs received over past 8 minutes	10
RX4 Signal Strength	7	157	164	160	(See RX1 Signal Strength)	8
Time Source	1	166	166	---	0=internal RTC, 1=GPS time	1
Channel B noise floor	5	167	172	170	Combined receivers noise floor for 162.025 (See “Noise Floors” in Appendix C.2 Metadata)	6
Unassigned bits	5	173	178	175	Available undefined bits	6
Rebroadcast Message	168	179	388	(See note 1)	All the original rebroadcast message’s bits (See note 2)	210
Rebroadcast Message CRC	16	389	408	390, 395, 400 & 405	CRC for the original rebroadcast message	20

Note 1: The Fixed “zero” bits inserted among the original rebroadcast message bits are bits 180, 185, 190, 195, 200, 205, 210, 215, 220, 225, 230, 235, 240, 245, 250, 255, 260, 265, 270, 275, 280, 285, 290, 295, 300, 305, 310, 315, 320, 325, 330, 335, 340, 345, 350, 355, 360, 365, 370, 375, 380, and 385. None of these bits are part of the rebroadcast message, and most importantly, they are not involved in calculating the original rebroadcast message CRC.

Note 2: To make use of the following rebroadcast message CRC, the 42 Fixed “zero” bits need to be removed and only the remaining 168 bits of the original message used to calculate the CRC.



APPENDIX E. STRUCTURE OF EXPERIMENTAL “PRDC,VDC-SENTENCE”

Standard AIS equipment does not output received AIS messages that fail the CRC test. Consequently, the NMEA 0183 standard does not contain an appropriate “sentence” to use to output the content of a corrupt AIS message. The NMEA 0183 standard does provide information about creating experimental sentences and instructions regarding the encapsulation of AIS messages in NMEA sentence data fields. This NMEA 0183 information was used to craft the following experimental sentence, and implementation of the sentence as part of the SM1680 receiver upgrade. The external laptop “Surveillance” software recognizes the “PRDC,VDC” sentence and properly decodes its contents. The following is a sample of SM1680 PRDC,VDC output and a description of the sentence’s data fields. The interested reader should refer to the NMEA 0183 version 4.1 for complete information about test sentences and AIS message encapsulation.

Sample of actual SM1680 output:

```
!PRDC,VDC,2,1,5,A,1,26,1E37,J5M2p1h0VB=j@1<Tq40009Tf@P03P012WS61A0000jV,0*65
!PRDC,VDC,2,2,5,,,,,VH09R2NE8k`JABC<@08790tPE00pG,0*08
```

Description of the PRDC,VDC sentence (Also, see NMEA 0183 version 4.1, section 5.3.4.1):

```
!PRDC,VDC,x1,x2,x3,a1,x5,x.x,h--h,s--s,x4*hh<CR><LF>
```

Table E-1. Description of PRDC,VDC “Corrupt AIS Message” data fields.

ASCII	HEX	DESCRIPTION
“!”	21	<u>Start of Encapsulation Sentence.</u>
“PRDC,VDC”		<u>Address Field.</u> Proprietary Sentence created by USCG R&D Center for test purposes. The VDC indicates the encapsulated data field is that of an AIS message failing the CRC test.
“,”	2C	<u>Field delimiter.</u> Starts each field except address and checksum fields. When followed immediately by another comma (the delimiter for the next data field), this indicates no data in the field.
x ¹		<u>Total Number Of Sentences field.</u> Encapsulated information often requires more than one sentence. This field represents the total number of encapsulated sentences needed. This is a fixed length.
x ²		<u>Sentence Number field.</u> Encapsulated information often requires more than one sentence. This field identifies which sentence of the total number of sentences this is. This is a fixed length.
x ³		<u>Sequential Message Identifier field.</u> This field distinguishes one encapsulated message consisting of one or more sentences, from another encapsulated message using the same sentence formatter. This field is incremented each time an encapsulated message is generated with the same formatter as a previously encapsulated message. The value is reset to zero when it is incremented beyond the defined maximum value. The maximum value of this field is 9. This is a fixed length.
a ¹		<u>AIS Channel.</u> This field identifies the AIS channel upon which the encapsulated message is received. A = AIS1, 161.975 MHz.; B = AIS2, 162.025 MHz. This may be a null field when multiple sentences are used.
x ⁵		<u>Message of Interest Error Condition.</u> This field identifies the nature of the AIS message corruption. The maximum value of this field is 9. This may be a null field when multiple sentences are used. 1= Received AIS message had the correct “Message ID;” and the expected number of bits; however, the message failed the CRC test. 2 = Received AIS message had the correct “Message ID;” and the number of bits in the message fell within an acceptable tolerance; however, the message failed the CRC test. 3 = Received AIS message had the correct “Message ID;” however, the number of bits ran past the maximum expected. No CRC test was performed. 4 to 9 = undefined.



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Table E-1. Description of PRDC,VDC “Corrupt AIS Message” data fields” (Cont’d).

ASCII	HEX	DESCRIPTION
x.x		<u>AIS Message Type.</u> This is the number of the AIS “Message ID” for which this sentence relates. For the Extended Range task, this should equal “26.” This may be a null field when multiple sentences are used.
h--h		<u>AIS Message CRC.</u> For error conditions (x ⁵) 1 and 2, this is a string of 4 hexadecimal symbols (0 to F) containing the last 16 bits of the corrupted message. This should be the 16 CRC bits of the message. For error condition 3, this is a string of 6 hexadecimal symbols containing the last 24 bits of the corrupted message. The first 4 symbols should be the 16 CRC bits and the last 2 symbols the “corrupted” End Flag of the message. This may be a null field when multiple sentences are used.
s--s		<u>Encapsulated AIS message.</u> Follows AIS message CRC and contains a portion or all of an encapsulated AIS message, depending on the length of the AIS message. The extended range Type 26 message does require two PRDC,VDC sentences. The encapsulated data field shall always be the second to last data field in the sentence.
x ⁴		<u>Fill Bits field.</u> This field represents the number of fill bits added to complete the last Six-bit coded character. This field is required and shall immediately follow the encapsulated data field. To encapsulate, the number of binary bits must be a multiple of six. If it is not, one to five Fill Bits are added to the encapsulated message. This field shall be set to zero when no Fill Bits have been added. The Fill Bits field shall always be the last data field in the sentence. This shall not be a null field.
“*“	2A	<u>Checksum Delimiter.</u> Follows last data field of the sentence. It indicates that the following two alphanumeric characters show the HEX value of the Checksum.
hh		<u>Checksum Field.</u> The absolute value calculated by exclusive-OR’ing the 8 data bits (no start bits or stop bits) of each character in the Sentence, between, but excluding “!” and “*.” The hexadecimal value of the most significant and least significant 4 bits of the result are converted to two ASCII characters (0-9, A-F (upper case)) for transmission. The most significant character is transmitted first. The Checksum field is required in all transmitted sentences.
<CR><LF>	0D 0A	<u>Terminates Sentence.</u>

The bits of the entire corrupted message are contained in the s--s data field. For a complete explanation of how each character of the s--s represents 6 bits of the AIS message, refer to the NMEA 0183 version 4.1 standard. Briefly, the following table lists the binary bits represented by each character. The content of the AIS message begins with the first character of the “s--s” string and the first AIS message bit is the left most symbol in the following table. For example, the first character of the SM1680 output, shown above, is “J.” The binary field that “J” represents can be found in Table E-2 below. It is “011010.” The left most bit, “0,” is the first bit of the received AIS message, and the right most bit, “0” is the sixth bit of the AIS message. The next character of the “s--s” string above is “5.” The binary field that “5” represents can be found in Table E-2. It is “000101.” The left most bit, “0,” is the seventh bit of the AIS message, and the right most bit, “1” is the twelfth bit of the AIS message. The “s--s” string continues in this pattern to represent the bits of the encapsulated AIS message.



Table E-2. "s--s" six-bit binary conversion table.

Valid NMEA Character	Binary Field	Decimal Value	Valid NMEA Character	Binary Field	Decimal Value
0	000000	48	P	100000	80
1	000001	49	Q	100001	81
2	000010	50	R	100010	82
3	000011	51	S	100011	83
4	000100	52	T	100100	84
5	000101	53	U	100101	85
6	000110	54	V	100110	86
7	000111	55	W	100111	87
8	001000	56	'	101000	96
9	001001	57	a	101001	97
:	001010	58	b	101010	98
;	001011	59	c	101011	99
<	001100	60	d	101100	100
=	001101	61	e	101101	101
>	001110	62	f	101110	102
?	001111	63	g	101111	103
@	010000	64	h	110000	104
A	010001	65	i	110001	105
B	010010	66	j	110010	106
C	010011	67	k	110011	107
D	010100	68	l	110100	108
E	010101	69	m	110101	109
F	010110	70	n	110110	110
G	010111	71	o	110111	111
H	011000	72	p	111000	112
I	011001	73	q	111001	113
J	011010	74	r	111010	114
K	011011	75	s	111011	115
L	011100	76	t	111100	116
M	011101	77	u	111101	117
N	011110	78	v	111110	118
O	011111	79	w	111111	119



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APPENDIX F. TEST REPORT FOR REBROADCAST SYSTEM

F.1 Introduction/Purpose

The following are the results of end-to-end functionality tests of the upgraded SM1680 receivers, AtoN transmitters, and prototype software – development work and tests performed at Shine Micro. These tests verify the: (1) sensitivity of the SM1680s; (2) reliability of the AtoN’s broadcast capabilities; (3) implementation of the experimental “VDC-sentence;” (4) implementation of the experimental type 26 “Extended Range” message metadata and rigid structure, and (5) proper operation of both the experimental rebroadcast and surveillance software running on the laptop computers.

F.2 Testing Scope

- Verify AtoN timing and power.
- Verify sensitivity of SM1680s.
- Verify reliable transmission from AtoNs.
- Verify VDC messages.
- Verify Rebroadcast GUI.
- Verify Surveillance GUI.
- Verify Metadata.
- Verify Rigid Structure.

F.3 Types of Testing Performed

The performance of the SM1680 receivers were tested using a standard Shine Micro production test (SWT-1682-001). The AtoN timing was evaluated using the combination of a SM161-R and oscilloscope. The overall end-to-end functionality was tested using a variety of signal attenuation levels to ensure the range of the complete system was evaluated. The detection of corrupted messages and resulting VDC-sentences tests were conducted with the SM1680 receivers input: (1) terminated; (2) receiving messages with good signal strength; and (3) with noise pulses added to the receiver’s input to purposely corrupt the AIS messages.

F.4 Hardware Setup

- Setup overview is provided in Figure F-1.
- Setup overview is provided in Figure F-2 for noise injection to create corrupted messages.
- The Rebroadcast PC is connected to the Rebroadcast SM1680 through TCP/IP port 50050.
- The Rebroadcast PC is connected to the two AtoN units using a USB to RS-232 serial splitter.
- The AtoNs are connected to a 12V DC power supply (not shown).
- All VHF RF connectors are type N except for the AtoNs VHF output which is RP-SMA.
- The Surveillance PC is connected to the Surveillance SM1680 through TCP/IP port 50050.
- Note that the SM1680 and AtoN units connect to a GPS antenna; which is not shown.



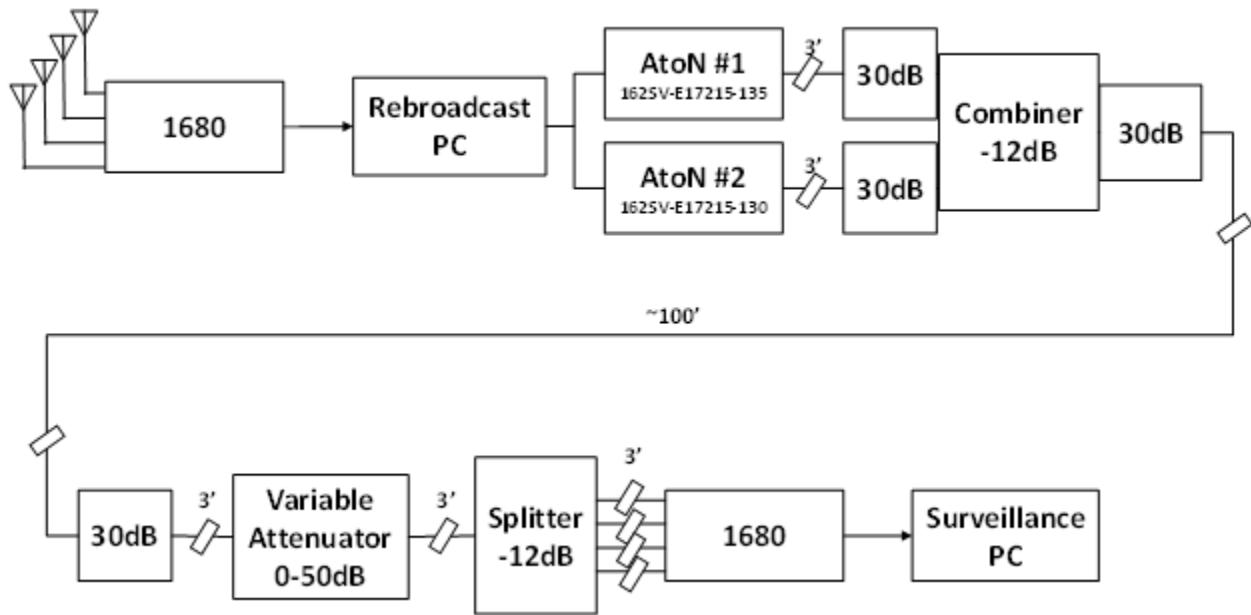


Figure F-1. Equipment configuration for end-to-end functionality testing without the injection of message corrupting radio interference.

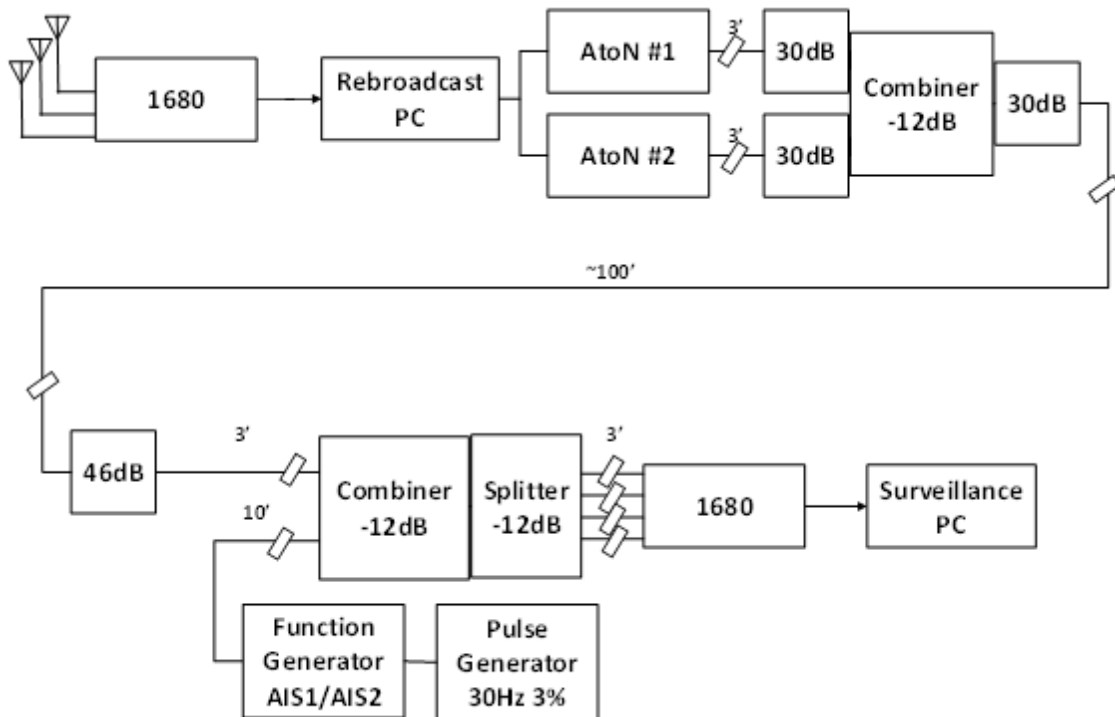


Figure F-2. Equipment configuration for end-to-end functionality testing with the injection of message corrupting radio interference.

F.5 Software Used

The Rebroadcast PC operates using the Ubuntu (Linux) operating system. The experimental rebroadcast software and version used during these tests was “RebroadcastGUI.py (v1.1.2)” which is written in Python. This program filters the messages provided by the SM1680, captures metadata about each received message, repackages and combines the messages and metadata as a “payload” for broadcast using a message 26, and sends selected payloads to AtoN #1 and AtoN #2 using a standard NMEA 0183 “MEB-sentence.” During operation, the display shows the: (1) PTI-request from each AtoN (A PTI-request is the AtoN’s notification that it is ready to accept another MEB-sentence); (2) MEB-sentence that the Rebroadcast PC provides the AtoN; and the standard VDO-sentence provided by the AtoN (which confirms that the payload of the MEB-sentence was broadcast in an AIS message (Type 26).

The Surveillance PC also operates using the Ubuntu operating system. The experimental surveillance software and version used during these tests was “SurveillanceGUI.py v1.0.2” which is written in Python. This program displays raw AIS data, encapsulated strings, and decoded Metadata.

Both the Rebroadcast SM1680 and the Surveillance SM1680 use a software upgrade custom designed and coded for this project (v1.1.9_CG.4). The AtoNs are using a standard Shine Micro version (v0.7.10b).

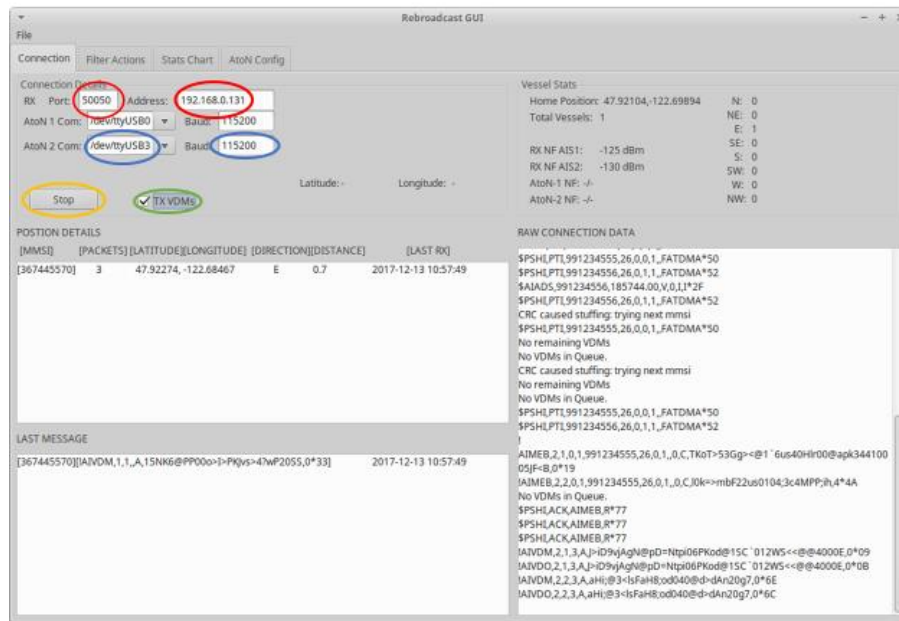
F.6 Software Setup

The following briefly introduces the rebroadcast and surveillance software’s control and displays. For full details see the “Sonalysts System Instruction Manual.”

With hardware setup as described above, run RebroadcastGUI.py on the Rebroadcast PC. Set the “RX Port” to 50050 and the IP address to the address shown on the rebroadcast SM1680’s “Config” screen.

Use the drop-down menus to select the correct “AtoN 1 COM” and “AtoN 2 COM” USB ports and click “Start.” Make sure the baud rate is set to 115200 for each AtoN. In order to rebroadcast the messages being received, click the “TX VDMs” checkbox (See Figure F-3.).

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Key:

IP Address and Port to access receiving 1680 (Port 50050)

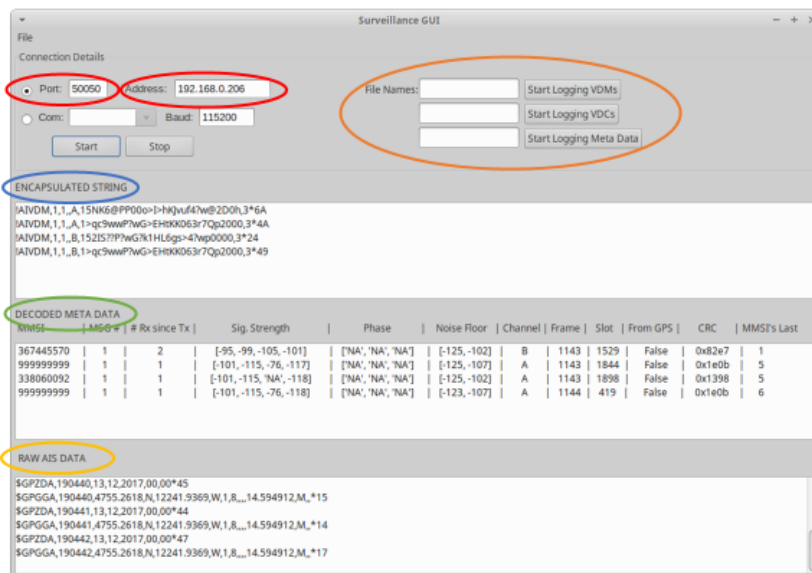
Drop down to select USB ports for the AtoN(s) and baud rate (set to 11520)

Turn on/off relaying VDMs

Begin/End Transmission

Figure F-3. Connection and control display of the rebroadcast software.

Run the SurveillanceGUI.py program on the Surveillance PC. Select the “Port” option under the “Correction Details” and enter 50050 in the box. Enter the IP address in the “Address” box. Make sure the address is as shown on the surveillance SM1680’s “Config” screen. Then click “Start” (See Figure F-4).



Key:

IP Address and Port to access Surveillance 1680 (Port 50050)

The VDMs relayed inside of the message 26s are here

Meta Data from VDMs relayed is here

Raw AIS incoming data feed

Enter a file name and click “Start Logging” to log VDMs, VDCs, and/or Meta Data

Figure F-4. Connection and control display of the surveillance software.

Both SM1680 receivers are upgraded with a special feature unique to this project. This feature permits a more detailed study of a selected “Message (type) Of Interest” or MOI. This feature is discussed in more detail in Appendix D. For the end-to-end functionality tests, the surveillance SM1680 MOI feature was setup as shown in Figure F-5.





Figure F-5. Surveillance SM1680 MOI configuration settings use during functionality tests.

F.7 Test Results by manufacturer

F.7.1 AtoN power and synchronization tests

Figure F-6 shows that the AtoNs are transmitting every 5 seconds correctly. Figure F-7 shows that both AtoNs are transmitting in the same slot, one is on channel A and the other is on channel B. AtoNs are set to 31dBm output and their actual measured output is:

Table F-1. AtoN output power and synchronization test.

AtoN	Power
162SV-E17215-130	31.5 dBm
162SV-E17215-135	30.5 dBm



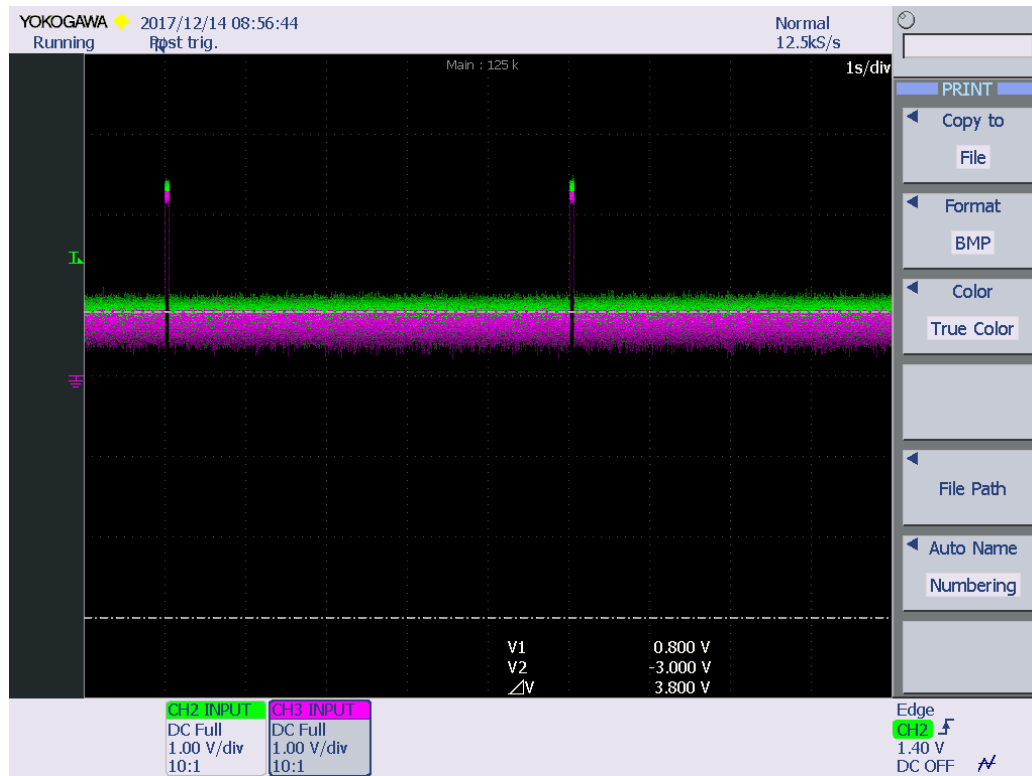


Figure F-6. AtoN #1 and AtoN #2 transmission synchronization.

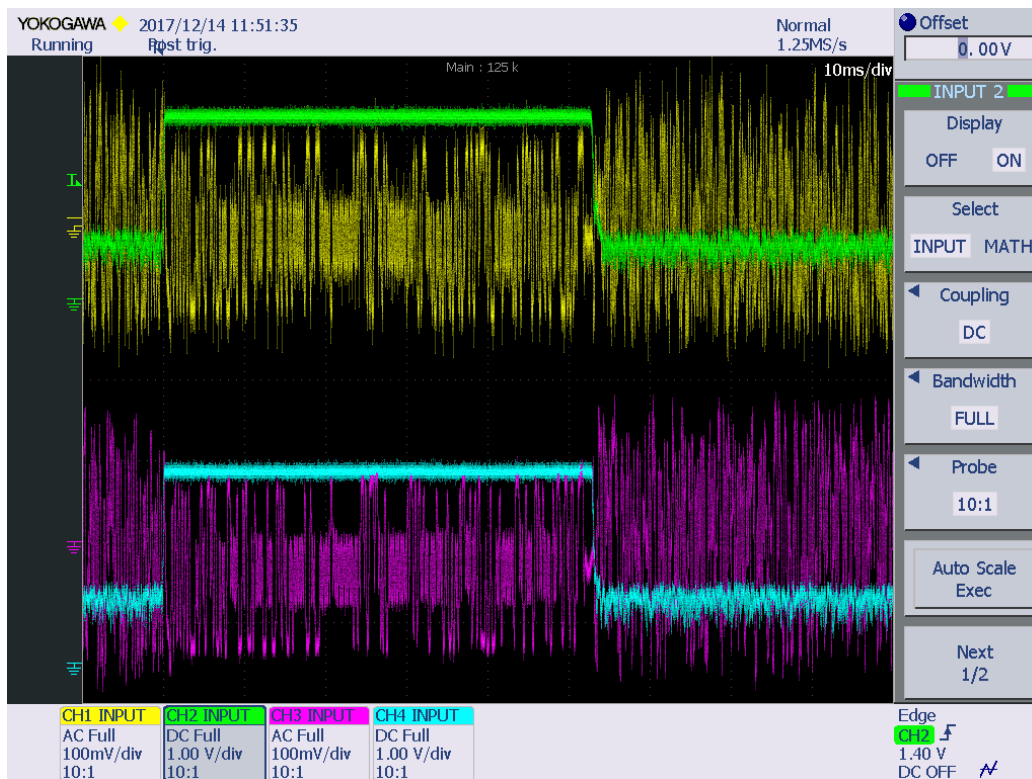


Figure F-7. AtoN #1 and AtoN #2 transmission synchronization with greater slot detail.



F.7.2 Surveillance SM1680 sensitivity test

This test verifies proper operation of the test setup (See Table F-2) and the signal strength level at which the Surveillance SM1680 will receive AtoN rebroadcast messages.

Table F-2. Surveillance SM1680 reception.

Variable attenuator (dB)	Combined Channel A (# messages)	Combined Channel B (# messages)	Individual Channel A (# messages)	Individual Channel B (# messages)	Channel A Comb. RSSI (dBm)	Channel B Comb. RSSI (dBm)
25	20	20	20	19	-106	-112
30	20	20	20	18	-111	-112
35	20	0	20	0	-115	nil
40	6	4	5	0	-119	-115

F.7.3 Corrupt AIS message detection and VDC-sentence output (Surveillance SM1680)

The “NMEA 0183 proprietary” VDC-sentence can be used to convey the bits of a demodulated AIS message when the message fails the CRC test. The VDC-sentence is used by the SM1680 to provide all message bits for three types of corrupt message “Error Conditions” (Also, see data field “x⁵” defined in Appendix E). The VDC-sentence contains the “Message of Interest (MOI) Error Condition” data field to indicate the type of message corruption (1, 2, or 3). The nature of each messages corruption are:

- Type “1” message corruption indicates the received message has the correct message ID and length, but fails the CRC test.
- Type “2” message corruption indicates the received message has the correct message ID; but the number of message bits is less than the configured length and within a bit-tolerance number defined by the operator, and
- Type “3” message corruption indicates the received message has the correct message ID; but no “end flag” is detected at the end of the number of bits expected in the message. In this case the CRC test could not be done.

The following examples are from actual test results confirming the detection of the three types of MOI error conditions. A complete description of the “!PRDC,VDC”-sentence (VDC-sentence) can be found in Appendix E. The “MOI error condition” data field is located between the “channel” data field and the “message type” data field. In the following examples it is highlighted with **yellow**.

MOI error condition 1 Example:

BAD_CRC; Correct Length confirmation: Below are two VDC-sentences with a MOI error condition of “1.” The two-part encapsulated message begins with a “J” (shown with **green** highlight). The “J” character represents the six bits (011010) which indicates the encapsulated AIS message is a Type 26 message; also, the expected length of the message is 432 bits.

!PRDC,VDC,2,1,5,B,**1**,26,E738,**J**>iD9w00gNh@01Le@5040;ocDE030012WP<d@P00005,0*6F

!PRDC,VDC,2,2,5,,,,aJM1W3>Ppic08h1>@0B078T2620g7,0*16

- Encapsulated message begins with a J.



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- $(43 + 29) \text{ char} * 6 \text{ bits} = 432 \text{ bits}$, no fill bits. Message is expected length.

MOI error condition 2 Example:

BAD_CRC; Length within Tolerance confirmation: Below are two VDC-sentences with a MOI error condition of “2.” The two-part encapsulated message begins with a “J” signifying a message 26, and the length falls within a 5-bit tolerance $427 < 428 < 432 \text{ bits}$ – an operator selected SM1680 configuration value.

```
!PRDC,VDC,2,1,2,A,2,26,C5EB,Jd0V1<>w:sU5S8JNhBEh:MGOVUwhs8Ftho<Q9CoRSW2,0*1F
!PRDC,VDC,2,2,2,,,,,soWd8?a6W2>fb18uMCNgJEWvtk5U@,4*38
```

- Encapsulated message begins with a J.
- $(43 + 29) \text{ char} * 6 \text{ bits} = 432 \text{ bits} - 4 = 428$, $427 < 428 < 432 \text{ bits}$. Is in the target range.

MOI error condition 3 Example:

NO_END_FLAG confirmation: Data was recorded until a VDC-sentence with MOI error condition of “3” occurred. When no “end flag” is detected following the last expected bit, the AIS “message” ends on the expected bit and the “message-bits” are coded into a VDC-sentence. In this test the limit was reached, no “end flag” was detected and the bits were correctly coded to create the encapsulated “message.”

```
!PRDC,VDC,2,1,6,B,3,26,DF68CF,J9kQL:oi8TtjeqjD9cww9DVKc@0vvJO<PNgcqgjAJsd,0*37
!PRDC,VDC,2,2,6,,,,,8Op?hig7TC1;vttuSW24Nv<=m3IgG,0*
```

- Starts with a J.
- $(43 + 29) \text{ char} * 6 \text{ bits} = 432 \text{ bits}$. Is the target length.

After confirming the VDC-sentences were constructed correctly, the surveillance SM1680 was tested with different levels of noise injected. Figure 8 shows how the number of detected VDC-sentences increases with noise injected into the receiver channels, and that the VDC-sentences are primarily the correct length. All VDCs are within the range 427-432 which is set up as Figure F-8 shows.

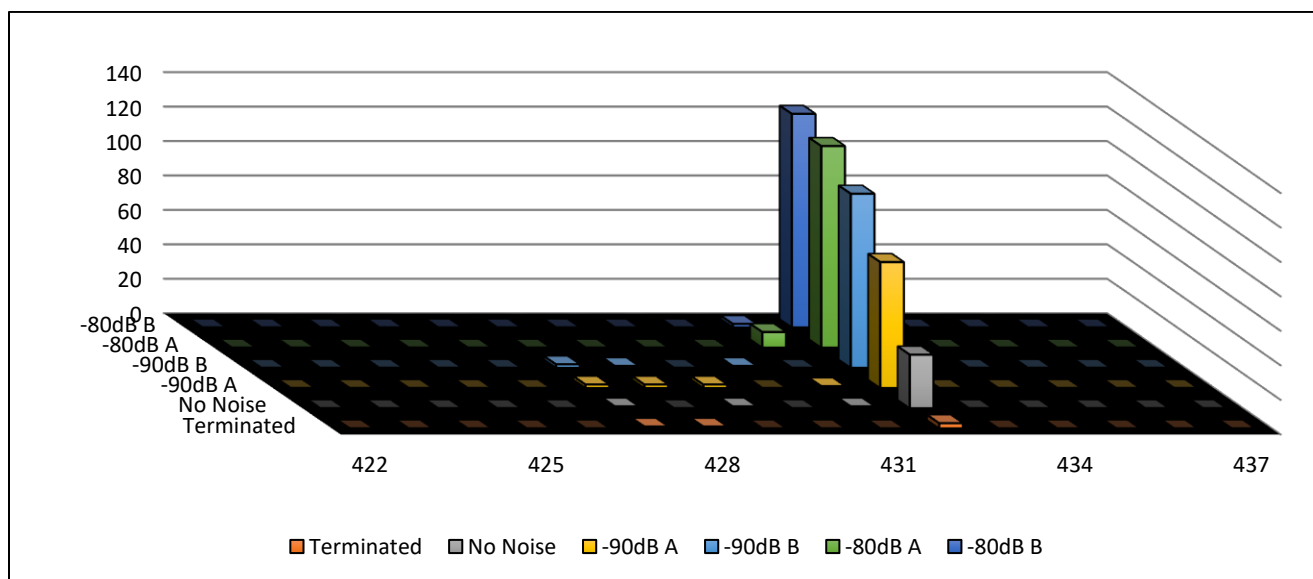


Figure F-8. Distribution of corrupted Type 26 2-slot messages when noise level is introduced.



F.7.4 Metadata and rigid structure verification

The following two NMEA 0183 VDO-sentences are an example of what the AtoN unit provides after the broadcast of an “extended range” message. VDO-sentences are shown in the “Raw Connection Data” textbox (See Figure F-3.). Below, the payload of an example VDO-sentence is shown coded in its binary form (Also, see Appendix D). The presentation of the bits is color coded as described in the “Note.” They show the bits of metadata, encapsulated AIS message, and the “zeros” of the rigid message structure.

!AIVDO,2,1,7,A,J>iD9vjQgNDhUgNt;@P2LKoc0<iCT01;F=<Asod0MsU,0*4F

!AIVDO,2,2,7,A,aHaHG3<m01P>I3h?040002p2I20g7,0*2B

First 40-bits of transmitted Type 26 Message (See Table D-1.):

0110100011101100010101000010011111101100

Following 368-bits “Binary data” portion of Type 26 Message:

1010 0 0011 0 1111 0 1111 0 101 0 0110 0 0010 0 1011 0 1111 0 1111 0 1111 0 0001 0 1101 0 0001 0
0000 0 0001 0 0111 0 0011 0 1111 0 1111 0 1011 0 0000 0 0011 0 0110 0 0101 0 1111 0 0100 0 0000 0
0000 0 1001 0 1101 0 1100 0 1101 0 0110 0 0100 0 1111 0 1111 0 1111 0 1100 0 0000 0 0111 0 1111 0
1110 0 1011 0 1001 0 1100 0 1010 0 1011 0 0001 0 1110 0 0011 0 0110 0 1101 0 1000 0 0000 0 0011 0
0000 0 0111 0 1101 0 0000 0 1111 0 0000 0 1111 0 0000 0 0001 0 0000 0 0000 0 0000 0 0000 0 0001 0
0010 0 1111 0 1010 0 010

Final 24-bits of transmitted Type 26 Message:

000010000000101111000111

Note: The following is the color coding used to identify the bits above:

Bits defined by ITU-R for the Type 26 message: (See Table D-1.)

Signal Strengths: (0, 104, 0, 98) add 20 and multiply by -1: (NA, -124, NA, -102)

Phases: all are 11111111 which are default for “no phase”

Reception Channel: 0 (AIS1, 161.975 MHz.)

Reception Frame: 177

Reception Slot: 1638

Number of MMSIs since last TX: 1

Number of Different MMSIs received in last 8min: 6

Five Spare Bits: (use TBD)

Average Noise Floor: (23,29) add 100 and multiply by -1: (-123, -129)

Time Source: false, no GPS lock

Recalculated encapsulated message’s CRC: 97D2

Data: The bits of an encapsulated Type 1 AIS message



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APPENDIX G. ANTENNA TEST RESULTS

G.1 Background

In their installation guidelines both the IMO and IALA describe AIS as a maritime mobile service and specify that every installation use a vertically polarized omni-directional antenna. This is both a space and engineering choice for mobile services. The space for an antenna on a mobile platform is limited and vertical antennas take up the least amount. From the engineering perspective, vertical antennas receive and transmit uniformly around the mobile platform in all directions. While the structure of the ship and other vertical antennas may distort the actual radiation/reception pattern, the objective of hearing and being heard in all directions is achieved.

Changing a service from mobile-to-mobile communications to point-to-point communications is a huge engineering change even if the technology used to do the communications stays the same. The objective of this task, to improve the AIS radio-link between a repeater site and the existing infrastructure changes the engineering of the radio-link to a point-to-point communications project. This literally opens a new book with respect to the engineering issues and options, and most of the options have to do with the selection of the antenna and its installation. The radio-link budget discussion (See Appendix B) concludes that the antenna changes alone can improve the radio-link by 15 to 20 dB. If the propagation path remains over water, this change alone can add ten's of miles to the radio-link range.

The radio-link budget estimates in Table B-1 have already been partially confirmed by earlier USCG R&D Center field demonstrations where directional vertically polarized antennas were used for long range reception of AIS messages; and those demonstrations only improved the gain of the reception antenna. So an early conclusion taken from this past work would be to always locate the repeater such that the radio-link between the repeater and existing infrastructure is across a water path. However, a water path is not always available. Point-to-point communications over land paths raises noise and obstruction issues not encountered over a water path. The observations of AIS signals from vessels in areas like the Alexander Archipelago in Alaska suggest land is a significant factor in blocking signals. Overcoming point-to-point issues across land will be a combination of careful site selection, antenna selection, and antenna installation. This task takes an initial look at antenna options.

G.2 Objectives

Previous R&D Center long range AIS tests and demonstrations were done using vertically polarized antennas. Vertical polarization was used because improving the reception of mobile AIS units was the objective, and the literature and earlier field experience suggested using the same polarization for antennas at each side of a radio-link. The literature suggests that, under ideal condition, there could be a 20 to 30 dB reduction in signal if the antennas are not the same polarization. This signal reduction is called cross-polarization isolation, and while it is not ignored completely, antenna specifications do not comment on it specifically. Cross-polarization isolation value is not found on the typical antenna specification sheet. It receives more attention when the antenna is designed for use in space; but those antennas tend to be custom designed for a specific satellite purpose.



This task investigated the cross-polarization isolation between different directional antennas and also the AIS signals radiated from vessels. The results are of interest for two reasons. First, if the point-to-point communications needs to use higher power to overcome the radio-link path loss, it would be helpful if the power increase did not have a detrimental effect on the local AIS operation. If the cross-polarization isolation is 15 dB between vertical and horizontal polarization, transmitting a 400 Watt signal using horizontal polarization should appear to be a 12.5 Watt signal to standard AIS where the antennas are vertically polarized (12.5 Watts is 15 dB less than 400 Watts).

Second, if the difference between horizontal and vertical polarization is greater than 10 dB, it may be possible to separate two simultaneous signals of the same strength and using the same channel if one is horizontally polarized and the other vertically polarized. AIS is a frequency modulated signal, and frequency modulation has the ability to “capture” the demodulation process. This means the stronger signal will appear to be the only signal on the channel if the signal difference between the two signals is above a certain threshold. This could allow two signals of equal strength to be received at the same time if the signals are received cross-polarized. The IEC standards do have a test for an AIS receiver’s “capture ratio.” The IEC recommendation is that the packet error rate shall be no more than a 20% when the desired signal is -104 dBm and the unwanted signal is -114 dBm. This is a 10 dB capture ratio. This suggests that a cross-polarization isolation of greater than 10 dB would offer the possibility for using simultaneous signals on the radio link.

G.3 Cross-polarization and Gain Test Results

Cross polarization tests were conducted using two different antennas at the USCG R&D Center in New London, Connecticut and a reference antenna and Class A AIS unit installed on Fishers Island, New York. The radio path between the R&D Center and Fishers Island site is primarily over water and provides an antenna separation of about 7 ½ miles.

The three yagi antennas are shown in Figure G-1. In Figure G-1, the upper left antenna is a 6-element Andrew DB292 shown mounted with vertical polarization. This is an antenna that is used by the R&D Center as an AIS reference antenna. It has an advertised forward gain of 9.5 dBd (or 11.6 dBi). The upper right antenna is a 3-element yagi shown mounted with vertical polarization. It is installed on a tower and was not changed through the test period. The signal used during testing was transmitted from Fishers Island using this antenna. The lower antenna in Figure G-1 is a 10-element Innovantennas Loop Fed Array (LFA) shown mounted with horizontal polarization. It has an advertised forward gain of 12.74 dBd (or 14.84 dBi) (More information about the “LFA” antenna can be found in section G.5, below.).





Figure G-1. Directional Yagi antennas used during cross-polarization isolation tests (See text.).

The cross-polarization tests were performed separately using the same mounting mast. During the tests, the forward gain of both the 6-element and 10-element antennas were also compared.

Several combinations of test were done and each time the results were about the same. The results of the tests showed between 15 to 17 dB of cross-polarization isolation. With the Fishers Island antenna mounted with vertical polarization, the signal of the Fishers Island Class A unit was 15 to 17 dB weaker using

horizontal polarization at the R& D Center than using vertical polarization. There was little difference in the results between the 6-element and 10-element antennas.

The forward gain comparison showed between 3 and 4 dB of improvement. The 10-element LFA Yagi had 3 to 4 dB more forward gain than the DB292 Yagi. Since this is about the difference published in their respective specification sheets, the absolute gain figures given in the specifications are an accurate description of each antennas actual gain.

G.4 Antenna Test Summary

The cross-polarization isolation between the gain antennas (15 to 17 dB) suggests there is promise in investigating further the idea of simultaneously multiplexing AIS signals on the same channel, in particular, at greater separation distances. The delivered instrumentation (software and transmitters) have the ability to create the test signals needed for this type of test. If testing shows that it is possible to multiplex cross-polarized signals, the next step would be to study the signal level stability of the horizontal and vertical signals. Over an extended radio-link, the signal fading characteristics of horizontal and vertical polarized signals may be different. If this is found to be the case, and the fading differential is significant (in this case 5 dB may be significant), some method of dynamic transmitter power adjustment may be needed to keep the two signals at equal signal strengths at the reception site. The two delivered transmitters have the ability for software control of their power level. Fading experimentation using the delivered capability could be done.

The observation of local mobile AIS “signals-of-opportunity” using the gain antennas (in both horizontal and vertical polarization positions) did not provide results as clear as the tests with the Fishers Island signal. The cross-polarization tests between the gain antennas were performed with the antennas pointing towards each other. The observations of local AIS signals were done with the gain antenna pointed at Fishers Island. The ambiguity of the observations may suggest that cross-polarization isolation is sensitive to the directivity pattern of the antennas involved. This question should be investigated in future tests.

The gain comparisons between the 6-element and 10-element antennas was a very good result. Despite mechanical issues with the 10-element antenna, its unique design should continue to be evaluated, in particular, with its noise rejection qualities. It may also be beneficial to evaluate a shorter version (fewer elements and with less gain) if the noise rejection qualities prove beneficial. A shorter version (about 7 feet) would be a valuable reference antenna for future field trials and site surveys.

G.5 Detailed Information about the 10 Element Loop Fed Array Antenna

G.5.1 Comments about the antenna

As a result of our research, the search for a “quiet” (low noise) high gain AIS antenna lead to the “LFA Yagi” designed by Justin L. Johnson, a radio amateur (GOKSC, also see internet URL below). Justin developed a high gain Yagi design that sacrifices a little gain in order to minimize the antennas side lobe gain. This modeling adjustment results in a quieter antenna that reduces noise energy from unwanted directions and delivers better digital signal reception (the gain patterns are provided below). Justin offers commercial antennas using the LFA design through his company, Innovantennas. A 10-element LFA Yagi was purchased and used during the cross-polarization isolation testing described above (See Figure G-1.).



While the LFA electrical design seems good, the construction of the antenna is marginal. The material and construction methods that Innovantennas uses to fabricate the 15 foot long 10-element Yagi is lacking. This antenna would not survive the most modest coastal installation without being firmly supported at two boom locations. Before deploying this antenna, mechanical upgrades or complete component replacements are needed. For example, the boom should be one piece and a larger diameter. Also, more consideration needs to be given to how this antenna could be mounted off of a tower leg in the vertically polarized position without distorting its gain (and noise) pattern.

More information about the antenna can be found at:

<http://www.g0ksc.co.uk/> and <http://www.innovantennas.com/>

G.5.2 Description

[Note: The information in this section is from the Innovantennas website.]

The LFA (Loop Fed Array) Low-Noise Yagi is very different from the traditional dipole fed Yagi in many ways. Its primary benefit is unwanted noise rejection. The LFA has a rectangular shaped, full wave loop driven element that is laid flat on the boom between and in-line with the parasitic elements. Then there is the way in which the loop functions. The smaller end sections of the loop run parallel to the boom and are engineered to be 180 degrees out-of-phase with each other. This provides the same effect as is seen within ladder-line feeders – each side cancels the other out and minimizes side-lobe radiation. This results in highly suppressed array side lobes and side-on signal rejection. This feature also plays a role in reducing F/B (Front to Back ratio) and broad-banding of the antenna.

The following is a list of the key benefits the LFA Yagi provides:

- The closed loop system helps reduce the reception of man-made noise and static.
- The LFA Yagi has been carefully optimized in order to ensure a 50Ω feed-point. This ensures no matching loss and minimal resistive (Ohmic) loss.
- The LFA Yagi has an exceptional Front to Back ratio for a direct-feed, 50Ω Yagi. The array is highly insensitive to signals from behind the array.
- Another unique characteristic of the LFA Yagi is the excellent bandwidth the antenna possesses. This ensures very large portions of a given band can be used with little return loss.
- A very rare feature is the ability for an antenna to provide a stable level of directivity performance under a variety of weather conditions. This is a result of the LFAs constant impedance.
- For Earth-Moon-Earth and other weak signal modes, no other antenna comes close to the LFA. Search for the VE7BQH G/T Table and compare the LFA with other antenna designs.

Performance:

- Gain: 14.84dBi @ 162MHz.
- F/B: 25.37dB @ 162MHz.
- Peak Gain: 14.96dBi.
- Gain 10m above ground: 19.08dBi.



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- Peak F/B: 26.76dB.
- Power Rating: 5kw.
- SWR: Below 1.2:1 from 161.5MHz to 162.5MHz.
- Boom Length: 4.8m.
- Vertical Stacking: 2.8m apart.

Construction:

This antenna is made with a 5/8 inch (15.9mm) parasitic elements complemented by a driven loop of 1/2 inch (12.7mm) and 3/8 inch (9.525mm) diameter tube. It also has fully insulated elements that will ensure continuous high performance and ensures corrosion will not impact performance. Marine grade stainless steel is used throughout. N-type coaxial termination is provided on this antenna along with a UV resistant Rubber sealant (including applicator) in order to ensure all open connections can be thoroughly sealed before final installation. The boom is 1.5 inch square 16SWG aluminum.

Gain patterns of the 10-element LFA Yagi: (See below)



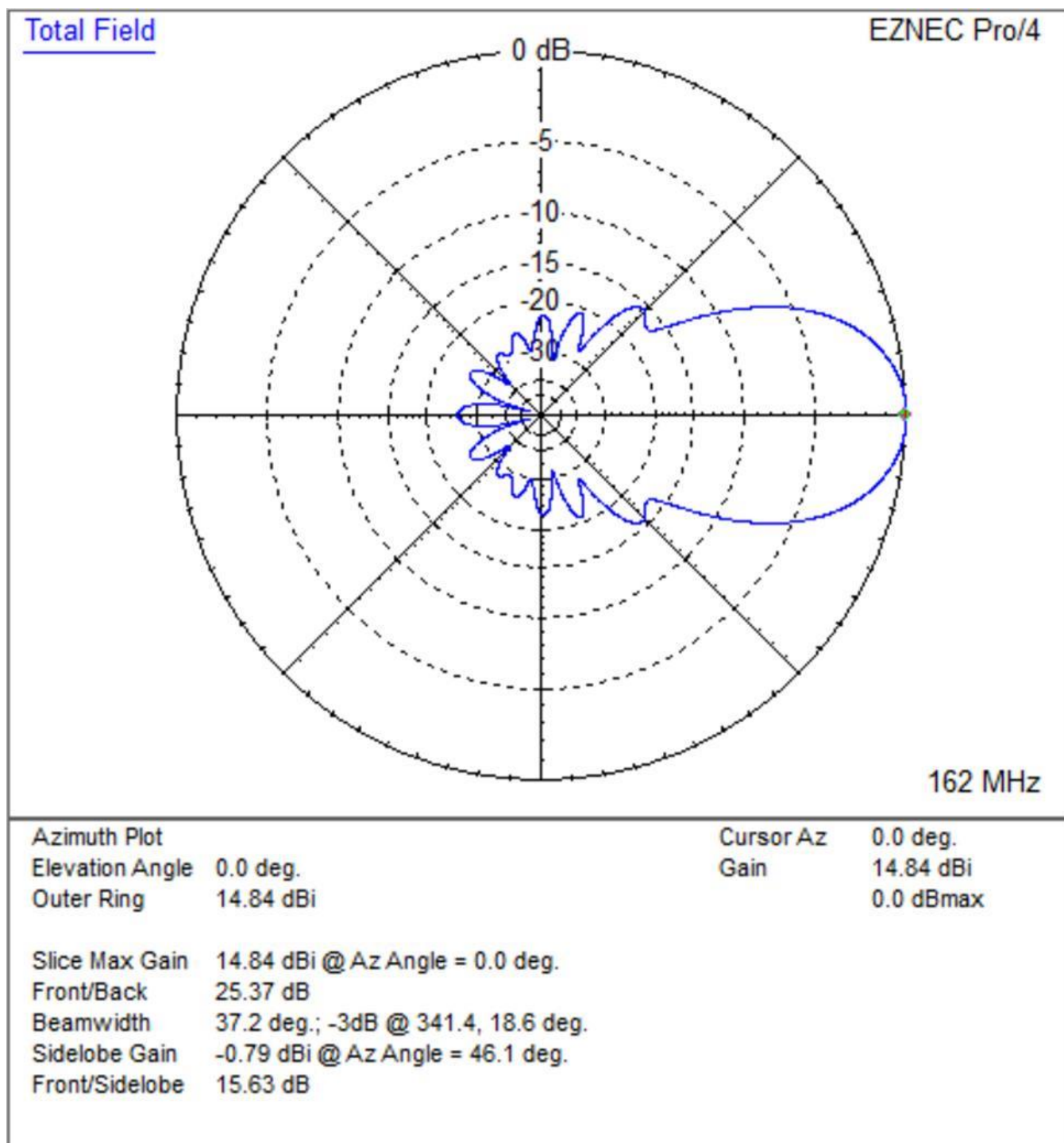


Figure G-2. Vertically polarized azimuth plot of 10-element LFA Yagi.



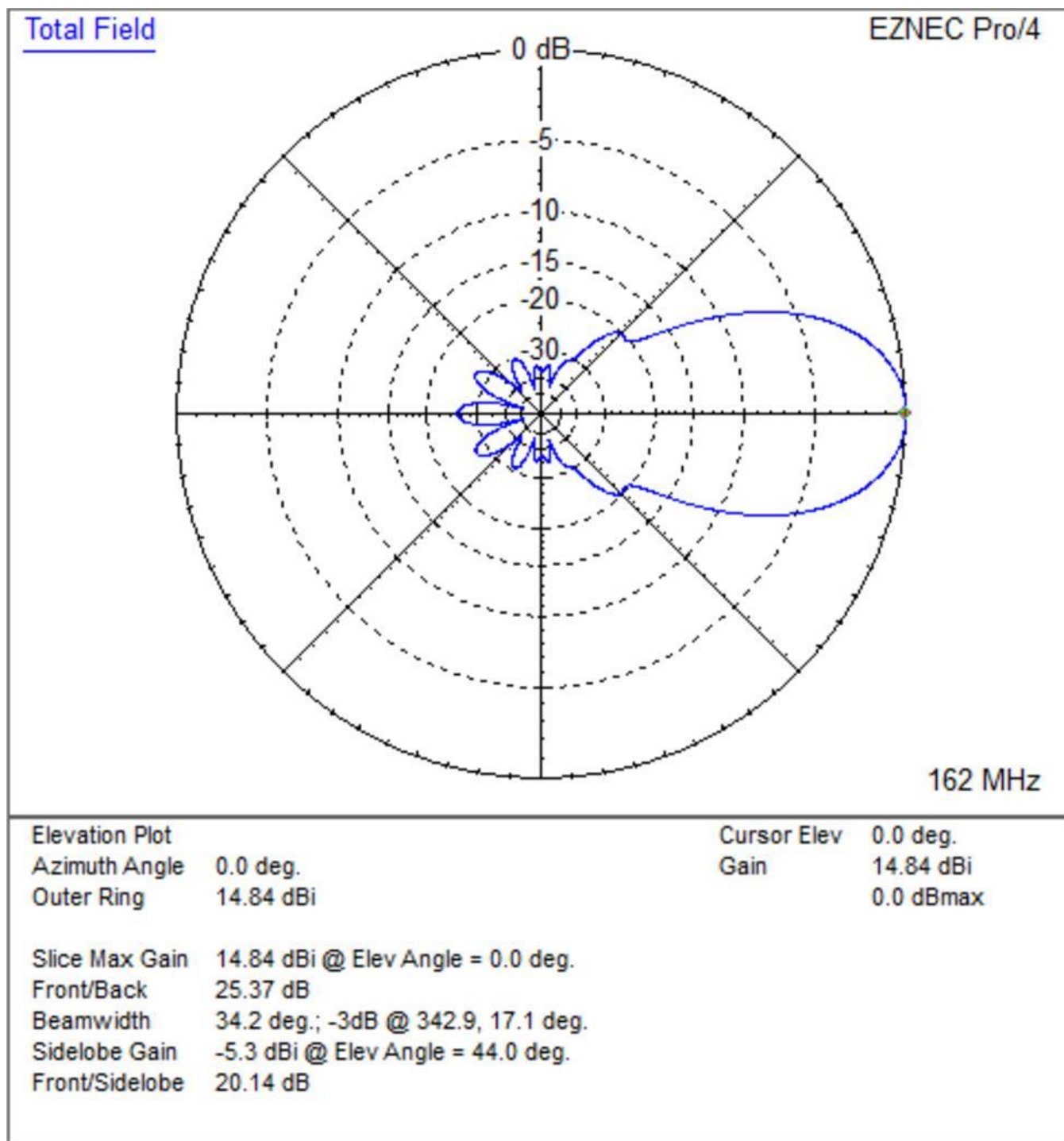


Figure G-3. Vertically polarized elevation plot of 10-element LFA Yagi.

